STANFORD RESEARCH INSTITUTE
Menlo Park, California 94025 · U.S.A.

Final Report *April 1977*

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PASADENA, CALIFORNIA 91103

CONTRACT 954546 UNDER
NASA CONTRACT NAS7-100
TASK ORDER NO. RD-4

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ABSTRACT

This report describes and illustrates a methodology for assessing the risk of back-contamination from Mars Surface Sample Return (MSSR) missions. The methodology is designed to provide an assessment of the probability that a given mission design and strategy will result in accidental release of Martian organisms acquired as a result of MSSR. This is accomplished through the construction of risk models describing the mission risk elements and their impact on back-contamination probability. A conceptual framework is presented for using the risk model to evaluate mission design decisions that require a trade-off between science and planetary protection considerations.

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FOREWORD

One source of critical concern in the exploration of space is the potential for planetary contamination. On the one hand, there is the risk of contaminating other planets through inadvertently transporting chemical and biological pollutants from Earth. Contamination of another planet could greatly impede subsequent research and could result in an irrevocable loss of scientific knowledge. Now that the technology exists for returning soil samples from another planet using unmanned spacecraft, a new, potentially dangerous prospect exists: the remote chance of inadvertently "back-contaminating" the Earth with extraterrestrial organisms.

Although there is currently no U.S. or international planetary protection policy for the return of extraterrestrial samples, an accepted policy concerning the contamination of other planets does exist. In 1966 the Committee of Space Research (COSPAR) of the International Council of Scientific Unions achieved an international agreement on quantitative objectives for probabilities of events that may contribute to planetary contamination. An upper limit on the probability of contamination of other planets was recommended. Planetary protection restraints for each NASA mission are established in such a way as to ensure conformance with the COSPAR standard.

Establishing a planetary protection policy for the return of samples from other planets will require deciding what is an acceptable level of back-contamination risk. The acceptable risk level is obviously extremely small, but it makes little sense to demand that only a zero level of risk be tolerated. Even meteors that enter the Earth's atmosphere carry with them some chance of contamination from extraterrestrial life forms. Sending astronauts to the moon and bringing back lunar samples presented some small risk of back-contamination.

The appropriate level of risk for a sample return mission can be established only through a recognition of the trade-offs between the potential costs of contamination and the value of the scientific achievement and information to be gained from space exploration. The costs of decontamination, sterilization, and other planetary protection measures may be significant, not only in terms of dollars but also in terms of delays, reduced system reliability, and limitations on mission capabilities. A framework must accordingly be developed to assist mission planners in evaluating sample return mission strategies. In particular, methodologies are needed for the accurate assessment of the probabilities and consequences of planetary contamination and of the value derived by society from the return to Earth of extraterrestrial soil samples.

Our central focus is on the decision framework needed by individuals and agencies responsible for decisions relating to the risk of back-contamination from Mars Surface Sample Return (MSSR) missions.

The framework we propose is a logical decision structure for integrating the factors that affect the decision: available alternatives, available information, and the preferences of society. The appropriate method for representing incomplete information is the language of probability theory. Preferences may be represented as trade-offs among science, economic costs, and the probabilities of contamination. The decision structure may then be used to determine the policies, strategies, and decisions that are consistent with the available alternatives, information, and preferences.

Development of some of the components of this framework is relatively straightforward. In particular, assessing the probability of a given mission design resulting in accidental release of Martian organisms is a well-defined problem. The major portion of this report is devoted to the description and illustration of a method for making this assessment. Other components are much more difficult to provide. For example, modeling the preferences of society for the trade-off between scientific objectives and the probabilities of back-contamination is a very difficult task. Although a brief discussion of how the trade-off preferences of society may be represented in the decision-making process appears in the report, additional research in this area is required.

Once a decision framework is established, the guidance required for decisions relating to sample return comes from inputs to the decision framework. Establishing these inputs, in particular, societal preferences for trade-offs, will not be an easy job, but the alternative approaches appear even less favorable. To quote Marvin Christensen et al.[1] of the Jet Propulsion Laboratory:

> Most knowledgeable engineers and scientists feel that the back-contamination problem should not be treated on a numerical basis as was the outbound program, at COSPAR's behest. Furthermore, indications are that the approach -- at least initially -- must be very stringent. The manner of defining how stringently quarantine should be treated, without expressing the degree of concern or caution needed by a single numerical constraint is very nebulous...In general, what is needed is a governing philosophy that is adhered to, and supported by, all levels of organizations involved.

We believe that a well-organized framework for decision making, together with an explicit and quantitative expression of the willingness of society to trade off risk against the benefits of space exploration, can provide the appropriate governing philosophy for MSSR mission planning.

ACKNOWLEDGMENTS

The authors wish to thank the many individuals at the Jet Propulsion Laboratory (JPL) who contributed time and effort to assist us in this research. We are especially grateful to Mr. Alan R. Hoffman for his aid and assistance throughout the project, to Mr. Harry N. Norton for information on and understanding of MSSR mission design, to Dr. Jack Barengoltz for help in assessing and understanding the problem of particle transfer during space vehicle rendezvous, and to Dr. Charles W. Craven who, as Project Manager of Planetary Quarantine at JPL, sponsored this research.

Dr. C. L. Yen of the Advanced Projects Group, JPL, earlier conducted a systems analysis of back-contamination risk from MSSR missions. We acknowledge wholeheartedly that her analysis was of considerable help to our own work.

We would like to acknowledge the contributions of SRI colleagues, especially Dr. D. Warner North who, as project supervisor, provided advice throughout the study and carefully reviewed this report; Dr. Stephen M. Barrager for discussions concerning the use and assessment of a contamination penalty; and Mr. Robert Korsan for his helpful contributions in the early phases of this effort.

Finally, we are grateful to members of the American Institute of Biological Sciences Planetary Biology and Quarantine Panel, who offered constructive criticism during a presentation of this research at the JPL Planetary Quarantine Program Review held January 18, 1977.

I SUMMARY

This report describes and illustrates a methodology for assessing the risk of back-contamination from Mars Surface Sample Return (MSSR) missions. In addition, a decision framework is described for assisting mission planners in making decisions that trade-off increased mission costs or decreased science capability for a lower risk of back-contamination.

1.1 Objectives and Scope

A complete assessment of the risk of back-contamination from an MSSR mission would require probability estimates for all elements in the risk chain, including the existence of life on Mars and the ability of Martian life forms to survive transport to Earth and to propagate in the Earth's biosphere. These issues were not addressed by the research described in this report. Rather, they are assumed to be true, and back-contamination is more narrowly defined. The methodology described is designed to assess the probability that Martian organisms collected and returned alive by an MSSR mission would, prior to their delivery to a Planetary Sample Receiving Lab (PSRL), be inadvertently released into the Earth's biosphere and would survive the release. Thus, probabilities of back-contamination computed using the methods described in this report are based on the assumption that viable Martian organisms are contained in the return spacecraft. These probabilities do not include the risk of back-contamination that might exist following transfer of the sealed sample, and associated responsibility, to the PSRL. To avoid misinterpretation, we refer to the methodology of this report as producing an assessment of the probability of "potential back-information" rather than an assessment of the probability of "actual back-contamination."

To illustrate the methodology, an analysis has been conducted of the risk of potential back-contamination for a "reference mission." This is a conceptual MSSR mission designed to return multiple unsterilized soil samples via a Mars orbit rendezvous with direct Earth entry. Since the reference mission has not been designed, the detailed numerical assumptions of mission design are purely hypothetical; however, an effort was made to obtain representative assumptions, subject to the time and budget constraints of the project. Consequently, the results may be viewed as providing a preliminary evaluation of the potential back-contamination risk of a MSSR.

1.2 Methodology

The proposed methodology for assessing the risk of back-contamination consists of the procedures and methods generally used by decision analysts for determining the probability of a rare event. The rare event, back-contamination in this case, is separated into the sequences of events that determine whether or not contamination occurs. Each event in the sequence is well defined and of sufficient probability to be comprehended without difficulty. The event sequences are represented as tree structures. Probabilities are assessed for each of the events in the tree structure, and the laws of probability theory are used in combining these probabilities to obtain the overall probability of back-contamination.

The tree structures represent systems models that capture for a particular mission design the available information and uncertainties that determine the probability of back-contamination. Additional models constructed to represent mission outcomes, in particular the scientific benefits of an MSSR mission and the consequences of contamination, may be combined to produce a framework for decision making. The usefulness of the decision framework is that it serves to organize and clarify issues affecting a decision relating to an MSSR mission by providing a means for modeling complex causal sequences, for dealing with uncertainties, and for characterizing the trade-offs among conflicting objectives that the decision may entail.

1.3 Major Findings

A probability of potential back-contamination of approximately 1 chance in 6,000 was obtained for the reference mission. Nearly all of the contamination risk is due to events occurring during Earth entry, and most of this is due to the risk of failure of the parachute system designed to slow the Earth-entry capsule. A number of essentially independent sources of risk contribute probability in the range of 10^{-6} to 10^{-5}. As a consequence, it is difficult to reduce the probability of potential back-contamination for the reference mission below about 1 in 100,000 without simultaneously improving or eliminating a large number of risk sources.

A preliminary analysis indicates that a lower probability of potential back-contamination, about 1 in 1 million, can be obtained if the entry mode chosen is orbital recovery rather than direct entry. The strategy would be to recover the sample in Earth orbit with the space shuttle, place it in a strong leakproof container, and then return it directly to an Earth-based PSRL. A somewhat higher mission cost may result for this alternative due to added complexity and the fact that a large velocity change would be required to put the capsule into a near-Earth orbit accessible to the space shuttle.

1.4 Methodological Findings

Analysis by tree structures is a flexible and efficient method for evaluating the risk of back-contamination from MSSR missions. In addition to providing a quantitative assessment of contamination probability prior to mission launch, the method of evaluation shows how this probability should be updated as information arrives during the course of the mission.

Sensitivity studies performed on the systems models constructed using this methodology may be used to identify areas of critical uncertainty. Sensitivity study results may also be used to suggest mission design changes for reducing back-contamination risk. Evaluation of the impact of proposed mission design changes may be easily accomplished by an appropriate expansion of the tree structures to account for the changes in effectiveness and reliability of the altered systems.

1.5 Recommendations

The primary emphasis of this report is on a methodology for constructing a systems model to assess the probability of potential back-contamination for a specified MSSR mission design, but attention is also given to the role of this model within a framework for making decisions relating to sample return. Our major recommendation is that the methodology for assessing contamination risk be extended and that additional methodologies be developed to provide the other components necessary for the realization of the decision framework.

The probability of back-contamination cannot be accurately determined until an assessment is made of the elements of the risk chain not considered in this report. Thus, Viking results should be used to develop models for the biological characteristics of potential Martian life. This work would require an interdisciplinary team including both qualified biologists and systems modelers.

The methodology for assessing contamination risk should be extended to permit the identification of a "best" mission design. This extension would be relatively straightforward. Finally, a methodology should be developed for assessing and operationalizing contamination penalties. The concept of a contamination penalty provides a logical means for consistently making trade-off decisions. However, additional research is needed to determine efficient methods for its assessment and use within a large technological project, such as an MSSR mission.

II METHODOLOGY

In this chapter we define the distinction between "actual back-contamination" of Earth by Martian organisms and the issue of "potential back-contamination," which is studied in this report. The chapter concludes with a description of a methodology for calculating the probability of potential back-contamination. An illustrative application of the methodology is presented in Chapter III.

2.1 Definition of "Actual Back-Contamination"

For this study, we define "actual back-contamination" of Earth by Martian organisms to have occurred when at least one Martian organism is released from controlled containment and reproduces in the Earth's biosphere using nutrients found on Earth for growth. For an MSSR mission to cause actual back-contamination of Earth by Martian organisms, the following must occur:

(1) Living organisms are found on Mars.

(2) Living Martian organisms are transferred to the return spacecraft.

(3) At least one organism survives the return trip to Earth.

(4) A surviving organism escapes the spacecraft (or receiving laboratory) confinement.

(5) It survives the escape.

(6) It is transferred to the Earth's ecosphere.

(7) It survives the transfer.

(8) It finds a niche in the Earth's ecosystem where it reproduces.

"Harmful contamination" implies two additional conditions:

(9) The contaminating organism has an undesirable effect on man or his environment.

(10) It is hard to combat.

2.2 Actual Back-Contamination Compared to "Potential Back-Contamination"

Rather than attempt to cover all of the issues listed above, this report addresses only issues 3, 4, 5, 6, and 7. Thus, the methodology is contingent upon certain assumptions about the existence and biological properties of Martian organisms. It could be extended to relax these assumptions, but the extension would require considerable assistance from qualified exobiologists. Since this work could profitably wait until the results of the Viking mission have been used to update the current understanding of the Martian environment, detailed modeling of the biological properties of Martian organisms (assuming they exist) was not included in this research. Instead, these conservative simplifying assumptions were made for assessment of the probability of back-contamination:

(1) Living organisms exist on Mars.

(2) Specific numbers of living Martian organisms are deposited in various areas of the return spacecraft. Chapter III and Appendix A give the detailed assumptions used in our illustrative calculation. (Our base calculation assumes 10^4 Martian organisms are contained in the return sample. The sensitivity of our results to changes in this assumption is explored in Chapter IV.)

(3) Organisms contained in sample canisters remain viable on the return trip to Earth. Specific assumptions are made about the viability of organisms that may be accidentally present in other locations, such as on the exterior of the spacecraft.

(4) Under all specified manners of release, the probability that any given Martian organism is able to find conditions sufficient for survival is independent of whether or not other released organisms survive. Given survival, the probability of growth is assumed to be unity. (These are very conservative assumptions. Using a survival probability for each organism of 10^{-3}, contamination is virtually assured if 10^4 or more Martian organisms are released to the biosphere.)*

In view of the conservative nature of these assumptions, we refer to the methodology as being designed to assess the probability of "potential back-contamination." The assumptions above imply that the probability

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*A relatively easy method for improving the growth model would be to note that there are certain overall <u>generic</u> traits that Martian organisms must have before they can survive on Earth; for instance, the ability to withstand Earth's temperature, pressure, and partial pressures of free oxygen, nitrogen and water vapor, as well as the ability to survive without ozone, ultraviolet radiation, and the uncommon chemical compounds found in abundance on Mars. The approach would be to assess the probability that organisms adapted for life on Mars would possess those traits. If the organisms did not possess those traits, they could not grow on Earth. No contamination would result, independent of the number of Martian organisms released to the Earth's biosphere.

estimate will be an upper bound for the probability of actual back-contamination. A more accurate assessment of the probability of actual back-contamination would take into account the probability of each of the conditions 1, 2, and 3 above, and a more realistic representation of the survival mechanism, which is very conservatively represented by condition 4.*

2.3 Mission Phases

For purposes of developing planetary protection policy, the MSSR has been described as consisting of three distinct phases.[1] Phase 1 consists of the trip from Earth to Mars and the landing of a descent vehicle on the Martian surface. Phase 2 begins with sample acquisition, includes transporting the sample from the Martian surface to Earth's vicinity, atmospheric entry of the capsule, recovery of the sample, and transportation to a PSRL. Phase 3 includes the initial quarantine and scientific investigation of the sample in the PSRL and ends with either certification that the sample is safe for release or, in the event that it is not released, with its sterilization.

The illustrative application of the methodology presented in Chapter III considers the risk of back-contamination due to Mission Phase 2; that is, events up to the recovery and transport of the sample to the PSRL. The method of analysis, however, is equally applicable to the risks of contamination following quarantine within the PSRL.

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*This refinement can be accomplished in a straightforward manner. The probability of actual back-contamination is approximately given by

$$P(AC) = P(L) \times P(S) \times P(C) \times P(G) \quad ,$$

where P(AC) = probability of actual back-contamination,
P(L) = probability life exists on Mars,
P(S) = probability samples contain Martian organisms that survive return to Earth,
P(C) = probability of potential contamination computed by the methods described in this report,
P(G) = probability returned Martian organism would reproduce on Earth.

A more accurate formula would allow P(G) to depend on the mode and location of release of Martian organisms. One may even want to recognize various levels of contamination.

A number of biologists hold that the probability of there being life on Mars that can survive in the Earth's biosphere is very small. Thus, the probability of actual contamination may be many orders of magnitude below the results computed in this report.

2.4 Proposed Methodology

Our procedure for assessing the risk of contamination from MSSR missions is a variation of the procedure generally advocated for determining the probability of rare events. The probability of a rare event is difficult to assess for two reasons. First, because the event is rare, individuals responsible for the assessment typically have little or no personal experience with the event. Second, there is a basic difficulty in distinguishing small probabilities. If an event is very unlikely, is its probability 1 in 10,000 or 1 in 100,000? If the consequences of the event are sufficiently important, such a distinction may be crucial.

The procedure generally used is designed to alleviate these two difficulties. Essentially, it involves breaking the rare event down into more familiar events whose probabilities can be evaluated more easily. The analysis is accomplished by identifying a set of mutually exclusive initiating events and the possible sequences of events that might follow each initiating event.

For the present problem, the rare event is back-contamination from an MSSR mission. A pertinent example of an initiating event is failure of a parachute system designed to slow Earth entry of the capsule containing the Mars sample. Parachute failure may initiate contamination through a number of event sequences, two examples of which are: (1) water impact, followed by capsule breakup, followed by survival of at least one organism; and (2) water impact, followed by no breakup, followed by capsule loss, followed by pickup and sample exposure by an unauthorized individual.

Figure 2.1 is an illustration of this approach as a tree structure. The far-left branch in the diagram represents the initiating event (parachute failure). Each branch point, or node, in the tree represents an event that may or may not occur following parachute failure. Each path through the tree represents a sequence of events. Some of the paths lead to a condition of contamination, and some do not. (Chapter III contains a detailed discussion of this figure.)

When the event is broken down in this way into sequences of more familiar events, the attention of the assessor can be directed toward the probabilities for each event in the sequence. The laws of probability theory may then be used to combine these probabilities to yield the probability of the rare event as a whole.

Analyzing back-contamination in this manner has several advantages:

- It allows the systematic elucidation of all possible occurrences relevant to back-contamination.

- The individual contingent events are much easier to imagine than one complex sequence of events taken together, and the contingent probabilities of simple events are easier to assess than an overall probability of occurrence of a complex series of events.

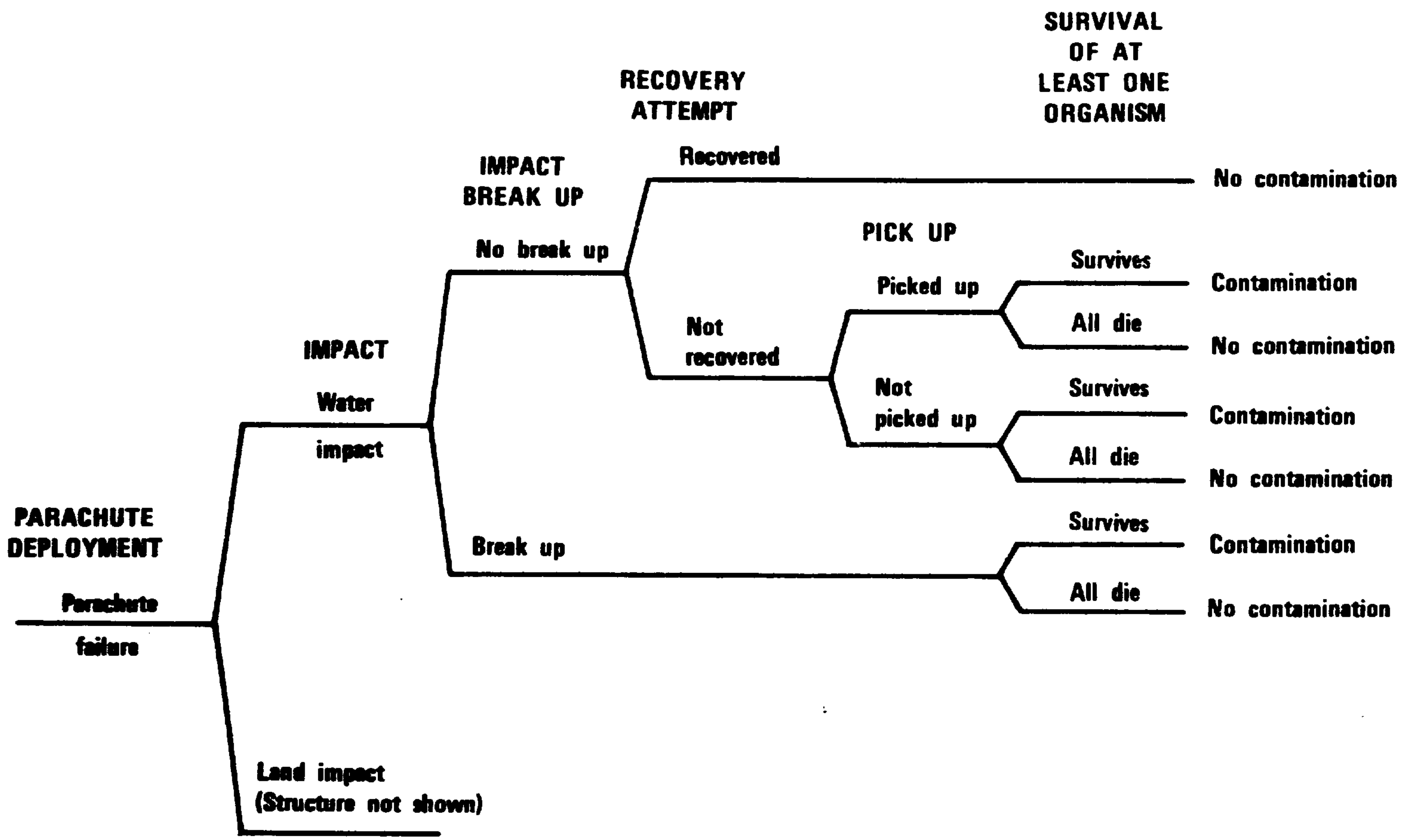

FIGURE 2.1 TREE DIAGRAM OF PARACHUTE FAILURE SEQUENCE

- One can integrate the knowledge of different experts in different fields.
- One can combine probability estimates of various types, based on historical failure rates, trajectory calculations given uncertainty in command and control operations, or an expert's subjective judgment.

2.5 A Comparison with Earlier Work

The methodology proposed in this report is essentially the same as that described in a previous report by Yen.[2] Yen's approach, like ours, is to break down the event of back-contamination into risk elements initiating sequences of events that may lead to the release of Martian organisms into the Earth's ecosystem. Most of the risk elements and many of the estimated event probabilities used in the example application in Chapter III are, in fact, taken directly from Yen's work.

The principal difference between the present approach and the approach followed by Yen is in application. As will be illustrated in Chapter III, our approach relies heavily on the graphical aid of tree representation to clarify and organize the assumptions made in the analysis. Representation of the possible sequences of events as a tree structure makes it easier to determine whether events may be treated as probabilistically independent, or whether the dependency among these events must be explicitly represented in the analysis. In particular, this approach makes it clear that the approximation often referred to as the Sagan-Colman formula[3] cannot be used to evaluate the risk due to equipment failures that result in large numbers of organisms being released into the Earth's environment, even if the probability of the release event is very small. Chapter III discusses this issue further.

In addition to our reliance on tree representation, the present approach emphasizes the use of sensitivity studies to indicate the areas for which extension of the analysis is most important. Chapter IV illustrates the use of sensitivity studies as part of the methodology for analyzing the risk of back-contamination. It is also shown that sensitivity studies may be used to identify the impact that improvements in reliability and other design changes can be expected to have on contamination risk.

III ANALYSIS OF THE REFERENCE MISSION

As described in Section 2.4, the methodology for assessing back-contamination probabilities requires: (1) identification of the possible sequences of events leading to potential back-contamination and their representation as tree structures, (2) assessment of the conditional probabilities of each of these events, and (3) use of the laws of probability to combine these probabilities to obtain the overall probability of back-contamination. This chapter illustrates the application of the methodology to a reference MSSR mission. Although we refer to the analysis as yielding a "probability of back-contamination," the reader should bear in mind that the quantity calculated is actually the probability of <u>potential</u> back-contamination, as defined in Section 2.2.

3.1 Definition of the Reference Mission

The reference mission is a conceptual MSSR mission; its basic structure was provided by Mr. Alan R. Hoffman of JPL, the technical monitor for this project. However, many of the mission details have been filled in by the authors. Since the risk of back-contamination is found to be quite sensitive to several of the detailed assumptions of mission design, specific analysis results must be considered illustrative rather than definitive. A more careful numerical evaluation, using the methods demonstrated in this chapter, should be performed for the actual mission design effort.

The reference mission is an unmanned Mars mission designed to return multiple unsterilized samples via a Mars orbit rendezvous with direct Earth entry. Choice of the rendezvous mode for sample return requires two different vehicles at Mars: an orbit vehicle inserted into orbit at arrival and a lander. While on Mars, surface samples collected by the lander are individually sealed inside sample canisters, which in turn are sealed inside a single sample container. The seals are designed to be gas-tight (brazed, for example). Following ascent and during docking, the sample container is passed to the Mars orbit vehicle and sealed inside the sample compartment on board the Earth-return vehicle. This seal is also designed to be gas-tight.

The return flight takes 340 days. The trajectory of the return vehicle is assumed to be biased away from Earth to reduce the risk of accidental impact, and four midcourse corrections are assumed to be required.

At Earth arrival, the Earth-entry capsule separates from the return vehicle and puts itself on the desired entry trajectory. After separation and deflection, the Earth-entry capsule is decelerated by the atmosphere to subsonic velocity. At an altitude of about 20 km. a parachute is deployed to further decelerate the capsule to terminal velocity. To improve reliability, two redundant parachute systems are used. Parachute deployment is based on static pressure. The capsule is recovered by an air snatch at an altitude of about 1.5 km. To reduce the likelihood of capsule loss in the event of a missed snatch, the capsule is equipped with a beacon, is designed to float, and will release a highly visible dye on high-velocity impact. Once recovered, the capsule is transferred to a PSRL.

Additional mission details are assumed as needed for the calculations and are noted in the following pages. In particular, Appendices A through D contain more detailed quantitative assumptions about mission design and the reliability of various mission components, systems, and operations.

3.2 Assumed Numbers and Locations of Martian Organisms

As stated in Chapter II, assumptions are made concerning the numbers and locations of Martian organisms on the return vehicle. The reasoning that led to specific assumptions is presented in Appendix A.

Figure 3.1 illustrates these assumptions. It is assumed that the sample canisters contain a total of 10^4 Martian organisms. It is also assumed that the process of sealing the canisters inside the sample container encloses an additional 100 organisms inside the container. The assumed presence of organisms on the outside of the container during rendezvous accounts for the contamination of the sample compartment on board the Earth-entry capsule by an additional 10 organisms. Finally, it is assumed that the exterior of the return vehicle may be contaminated due to transfer of organisms from the Mars ascent vehicle. However, it is assumed that this probability is sufficiently small, due to docking geometry, so that after ejection of the docking cone the expected number of organisms on the exterior of the return vehicle is assumed to be 0.02. Based on relative surface areas, 10% (0.002) of the expected surface organisms are assumed on the Earth-entry capsule.*

*Mathematically, the "expected number of Martian organisms" is defined as follows. Suppose that with probability P_0 there are no organisms present, with probability P_1 there is one organism, with probability P_2 there are two organisms, and so forth. The expected number of organisms, n, is then,

$$\sum_{i=0}^{\infty} iP_i$$

An expected number of organisms less than one implies that most likely no organisms will be present.

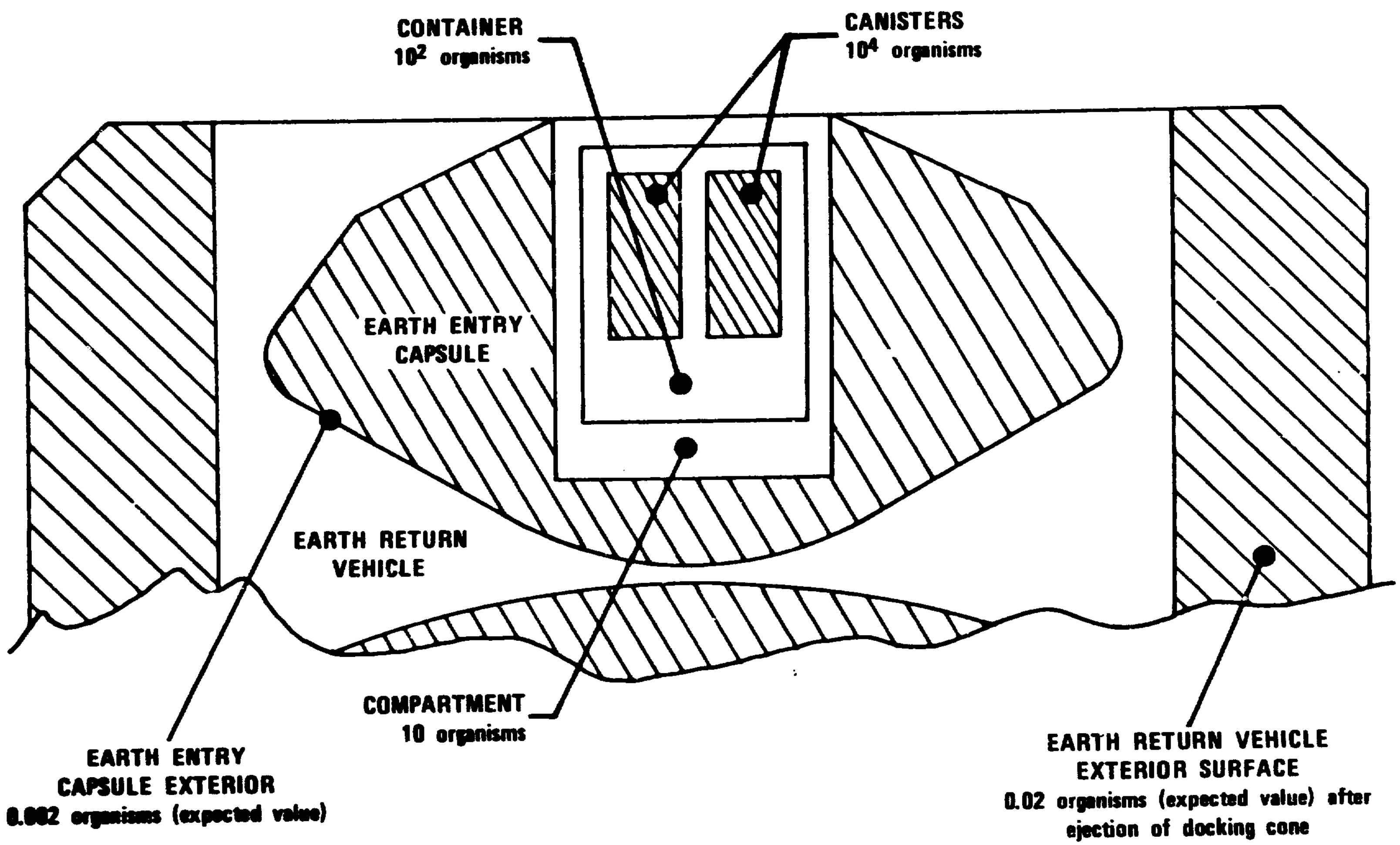

FIGURE 3.1 ASSUMED ORGANISMS ON RETURN VEHICLE

The sensitivity of the results of the analysis to these assumptions is investigated in Chapter IV.

3.3 Risk Elements

The first step in assessing the probability of back-contamination for the reference mission is to identify the mission events that initiate back-contamination risk and the resulting sequences of events that could lead to contamination. In all cases the possiblity of contamination can be traced to some initiating risk event. For example, faulty sealing of a sample canister may ultimately result in contamination through leakage of organisms into the Earth's environment. Or, transfer of surface organisms from the Mars ascent vehicle to the Earth-return vehicle during rendezvous may ultimately result in contamination from organisms brought to Earth on the surface of the entry capsule.

The reference mission was analyzed to identify the major risk events that may initiate a sequence of events leading to back-contamination (see Figure 3.2). The events depicted initiate a risk of back-contamination either because they influence the numbers and locations of Martian organisms on or inside the Earth-return vehicle, or because they are events for which a non-nominal outcome would increase the likelihood of the release of organisms. An example of the latter is parachute deployment. If the parachute system fails, the risk of contamination due to containment failure is increased substantially.

3.4 Modes of Back-Contamination

Contamination can occur by three distinct modes as a result of the reference mission. First, contamination can result from a major equipment failure causing the release of all or a substantial part of the sample into the Earth's biosphere. Failure of the parachute system followed by capsule breakup at impact is one example. Second, contamination may result from leakage of one or more of the biological seals. Third, contamination might result from surface contaminants, that is, organisms located on the exterior of the Earth-return vehicle.

To simplify the development of a tree diagram for the various sequences of events that potentially lead to back-contamination, each of these three modes of contamination was considered separately.

3.5 Major Equipment Failure

Figure 3.3 shows a gross tree diagram of the sequential and logical relationships among the most significant risk elements for major equipment failure. The first element is midcourse corrections. As noted in the description of the reference mission, the spacecraft return trajectory

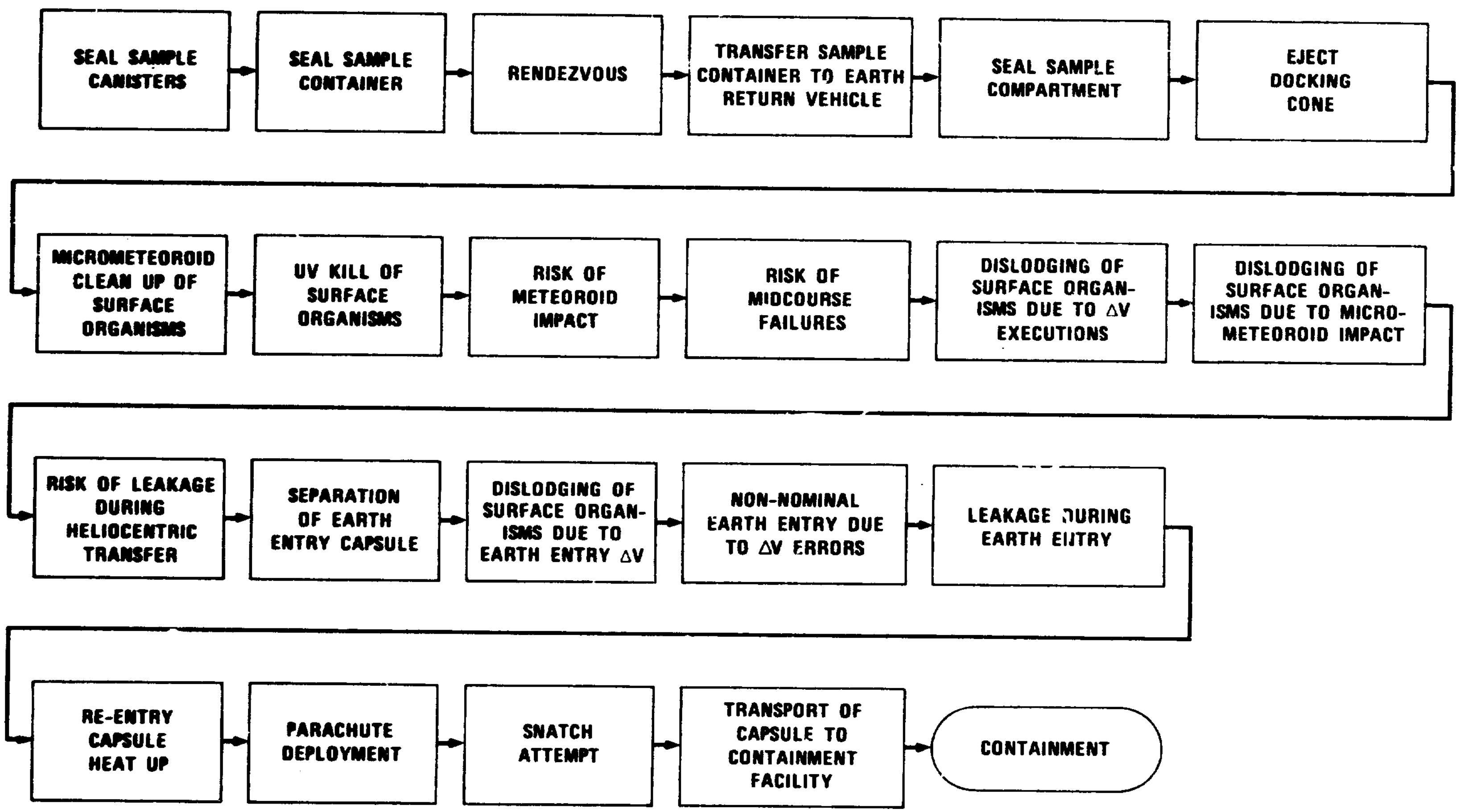

FIGURE 3.2 SEQUENCE OF MISSION RISK ELEMENTS

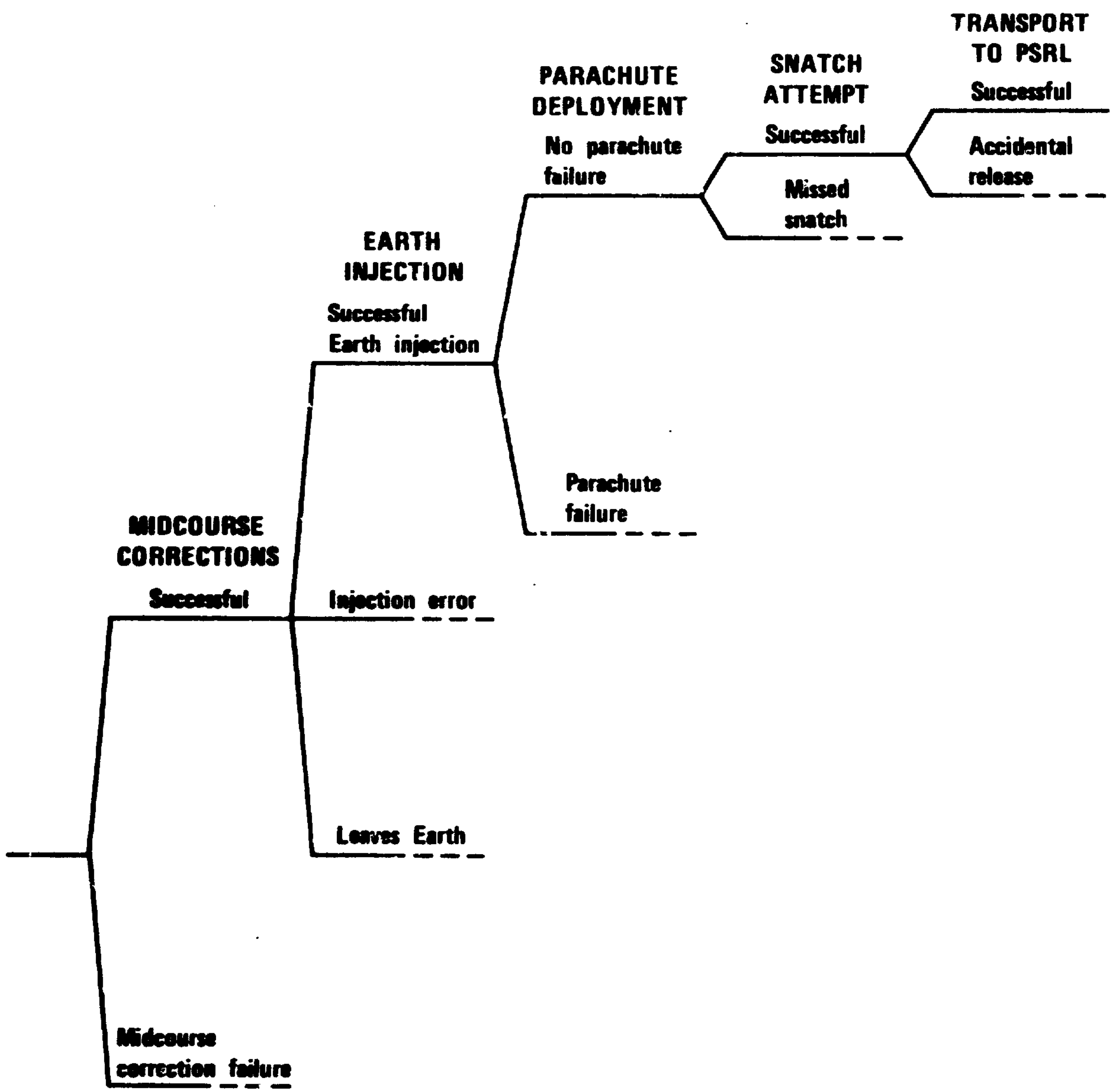

FIGURE 3.3 TREE DIAGRAM OF MAJOR EQUIPMENT FAILURE RISK EVENTS

will be initially biased away from Earth to reduce the chance of accidental collision. To obtain Earth capture, a series of velocity changes (ΔV corrections) are applied. These are considered a risk element because an incorrect midcourse correction (including loss of spacecraft control) may initiate a sequence of events leading to contamination. For example, Earth capture might be followed by uncontrolled atmospheric entry, capsule breakup, and survival of at least one organism.

The next risk element of major equipment failure is Earth injection. Earth injection occurs when a course correction causes the capsule to enter Earth's atmosphere at a velocity and angle that permit satisfactory operation of its heat shield and parachute system. Unsuccessful Earth injection will either result in no Earth capture of the capsule or atmospheric entry in a manner that is beyond the design limits of the capsule entry systems. The latter, of course, poses a risk of contamination.

Given successful Earth injection, the next risk element is parachute deployment. Recall that the design of the reference mission calls for two parachute systems for increased reliability. Assuming successful parachute deployment, the next risk element is the snatch attempt. Failure of the snatch attempt can result in contamination, for example, through breakage of the capsule upon surface impact. Finally, there is a contamination risk of accidental release during transportation of the sample to the PSRL.

One additional risk element shown in Figure 3.2 falls into the category of major equipment failure (i.e., a risk element that potentially initiates a sequence of events leading to contamination through unintentional release of all or a major portion of the sample into Earth's environment). This is the risk of meteoroid impact. The risk of meteoroid impact was not included in the gross tree structure of Figure 3.3 because the probability of this event was judged to be small relative to the other risks considered.*

3.5.1 Detailed Tree Diagram

Non-nominal outcomes for each of the risk elements (indicated by the dashed lines in Figure 3.3) would result in some probability of back-contamination. To determine the probability of contamination associated with each of the risk elements, the sequences of events that determine whether or not contamination occurs were identified and represented as detailed tree structure.

Figure 3.4 shows the detailed tree diagram developed for parachute failure. The tree structure simply lays out each possibility for each

*Yen[2] estimates the probability of meteoroid puncture of the spacecraft to be on the order of 10^{-7}.

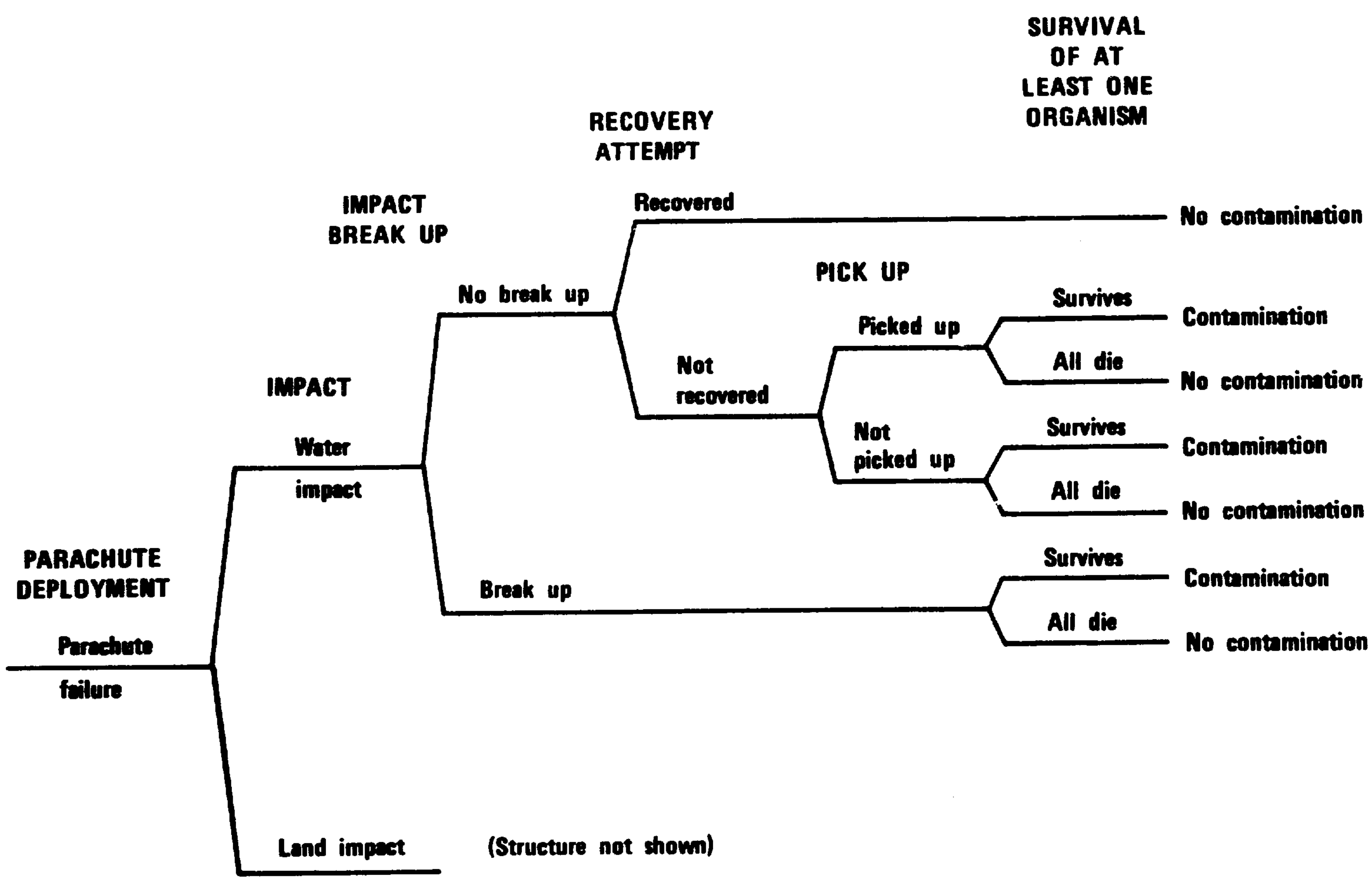

FIGURE 3.4 DETAILED TREE DIAGRAM OF PARACHUTE FAILURE SEQUENCE

event relevant to contamination that would follow failure of the parachute. If the parachute fails, the first pertinent event is whether the capsule hits water or land (land is defined as including all hard or soft nonliquid surfaces). This event is important because it influences the likelihood that the capsule and sample will break up and the likelihood that any released organisms will survive. (In Figure 3.4, only the detailed structure following water impact is shown; a similar structure, not shown, follows land impact).

If the capsule hits water, it either remains intact or breaks up. If it breaks up, then either all of the organisms die, or at least one survives. For the analysis, contamination was defined as the survival of at least one Martian organism. If all the organisms die, there is no contamination.

The sequence of events just described--water impact, followed by impact breakup, followed by survival of at least one organism--is one possible sequence of events that might follow parachute failure. This sequence corresponds to one path through the tree structure. Another possibility is water impact with the capsule remaining intact. At this point the tree shows that there are two possibilities: The capsule may or may not be recovered. If it is not recovered, contamination can result from pick up of the capsule and exposure of the sample by an unauthorized individual. If the capsule is not picked up, contamination can result from sample release due to the natural deterioration and physical decay of the capsule and sample container.

A detailed tree structure was constructed for the non-nominal outcomes for each of the risk elements in the category of major equipment failure. These detailed tree structures were then appended to the gross tree structure of Figure 3.3. Figure 3.5 shows the generic tree structure together with the detailed tree structure for the risk element parachute failure. The complete tree structure is shown in Appendix B.

3.5.2 Conditional Probabilities of Contamination

The various paths through the tree structure of Figure 3.5 represent a decomposition of the risk of contamination from major equipment failure into particular risk elements and sequences of events that may or may not lead to contamination. The next step in the analysis is to assess the probability of contamination associated with each of these possible sequences of events; that is, to assess the probabilities of contamination that should be associated with the end points of the tree structure. We refer to these probabilities as conditional probabilities of contamination. The rules of probability theory will then be used to combine the conditional probabilities into an overall probability of contamination.

As an illustration of how the conditional probabilities of contamination may be determined, consider one path through the tree structure of Figure 3.5: Suppose that midcourse corrections are successful, earth

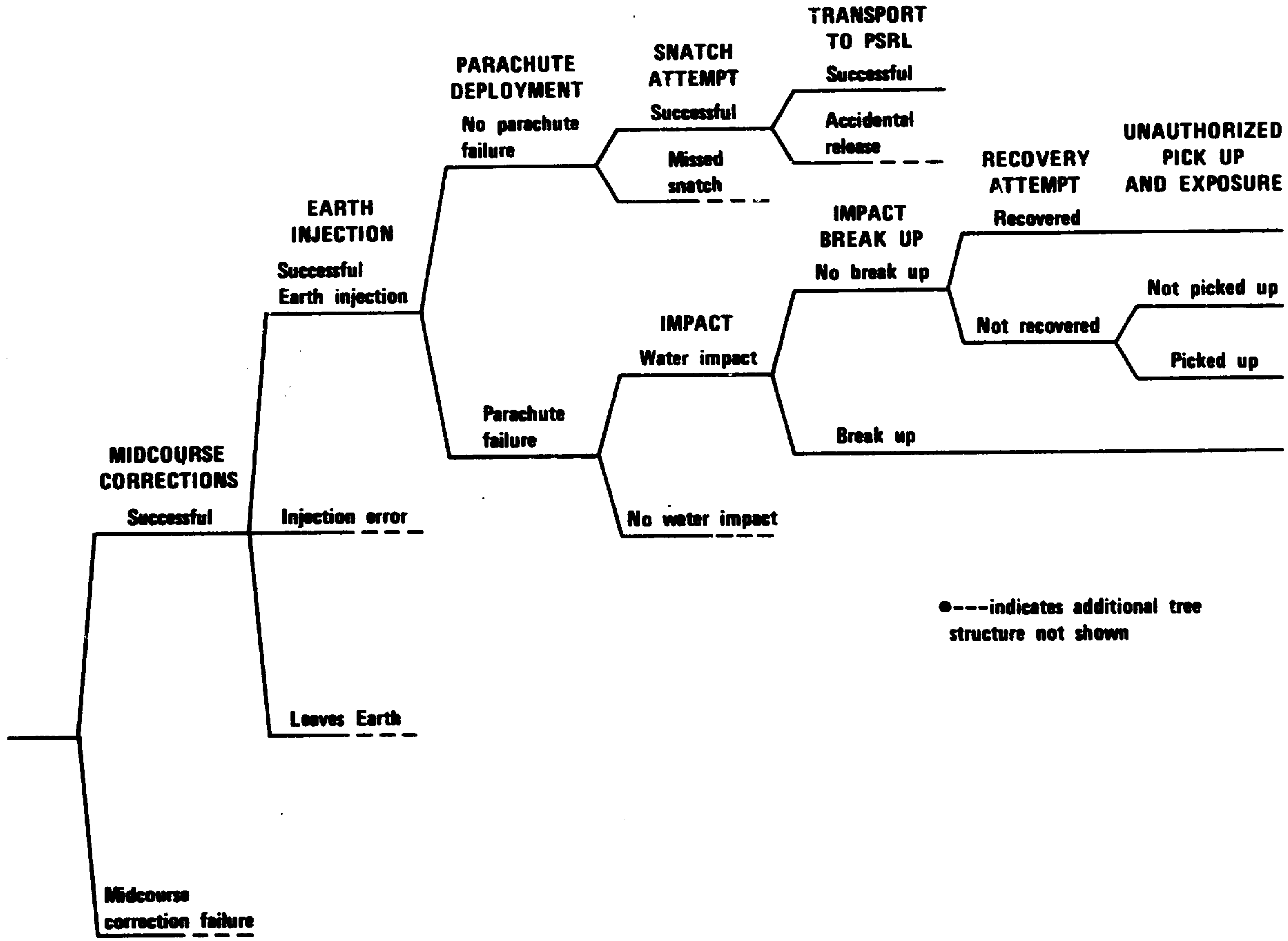

FIGURE 3.5 TREE DIAGRAM WITH DETAILED PARACHUTE FAILURE SEQUENCE

injection is successful, the parachute system fails, and the capsule hits water and breaks up. Capsule break-up is defined as an event during which all of the seals guarding at least one of the sample canisters are broken. Under these circumstances an appreciable fraction of the bioload of the capsule, assumed to be 10^4 Martian organisms, will be released. The conditional probability of contamination associated with this sequence is the probability that at least one of the organisms thus released will survive.

The probability that at least one of N organisms survives depends on the probability distribution describing the fraction f of Martian organisms that are able to survive on Earth under the given conditions of release. Assessment of this distribution is not an easy matter since it requires answers to questions of the following form: If a large number of Martian organisms were released on Earth in the manner described above, what is the probability that not more than 0.1% of those organisms would survive? Figure 3.6 shows the form of cumulative distribution that might be constructed from judgments of this type. It can be shown mathematically that this distribution is consistent with an expected fraction of surviving organisms of approximately 10^{-3} and a probability of roughly 10^{-2} that at least one organism survives.* Therefore, assuming the distribution of Figure 3.6, the conditional probability of contamination given successful midcourse corrections, successful earth injection, parachute failure, and water impact with break up is 0.01.

Application of this method for assessing the conditional probabilities of contamination would require the assessment of distributions for the fraction of surviving organisms for each path through the tree structure. Such assessments could be facilitated by the development of biological models for Martian organisms that reflect post-Viking knowledge of the Martian environment.

The computation of the probability that at least one out of a number of organisms survives can be simplified greatly if an assumption is made that the life or death of each organism is statistically independent of the life or death of any other organism. With this assumption, the only assessment that must be provided is the probability that any given organism survives. If this probability is p, then the probability that at least one out of N released organisms survives, denoted P_C, is given by the Bernoulli model:

$$P_C = 1 - (1 - p)^N \quad .$$

If we assume that any given organism released into the Earth's environment in the manner described above has a probability of survival of 10^{-3}, then

*For further discussions and an illustration of how this calculation is performed, see Harrison and North.[4]

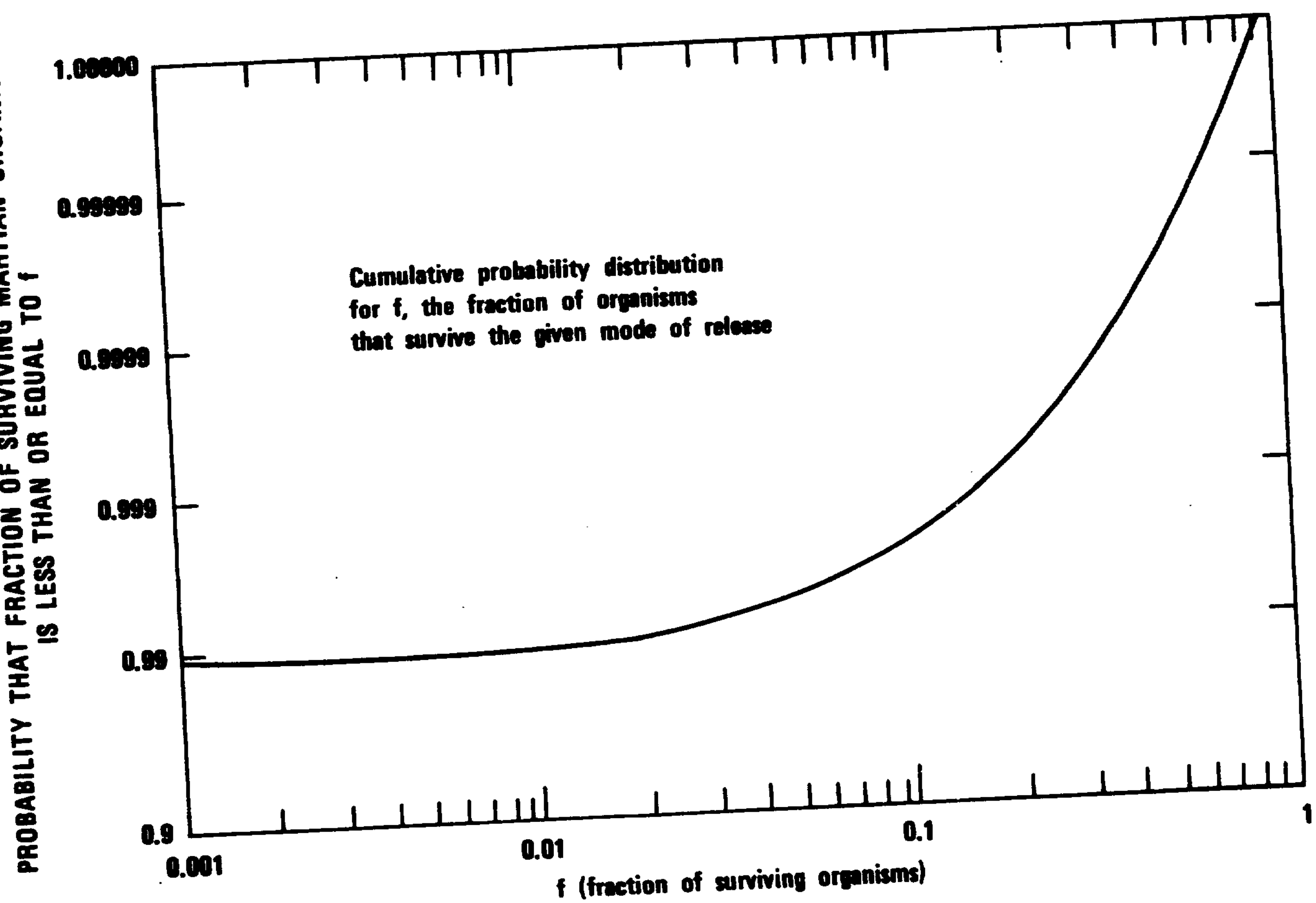

FIGURE 3.6 ILLUSTRATIVE PROBABILITY DISTRIBUTION FOR FRACTION OF SURVIVING MARTIAN ORGANISMS

if 10^4 organisms are released, the Bernoulli model gives a probability of $1-(4.5 \times 10^{-5})$ that at least one of those organisms survives. Thus, for this example the independence assumption yields a computed conditional probability of contamination for the given path that is roughly 100 times as large as that calculated using the more general model (1 compared to 10^{-2}). A consequence of the Bernoulli model is that if the number of organisms exceeds the reciprocal of the probability of survival by an order of magnitude or more, then the probability of contamination is nearly unity. Clearly, the assumption of independence is a very conservative one.*

An even simpler model that has been used[2] is the approximation to the Bernoulli model,

$$P_C = 1 - (1 - p)^N \cong p \times N \quad \text{for } p \times N << 1 \quad .$$

This approximation is sometimes referred to as the Sagan-Coleman formula.[3] Since for this example $p \times N = 10 > 1$, the approximation is obviously not valid in the analysis of the probability of back-contamination from major equipment failure.

Since data from the Viking mission were still accumulating at the time of this analysis, and since the development of biological models describing the possible survival mechanisms of Martian organisms on Earth was outside the scope of this study, the simplifying assumption of statistical independence was made for the analysis of the reference mission. However, note that a reduction in the calculated probability would be expected if more detailed calculations of the distributions for the fractions of organisms surviving were carried out.

Figure 3.7 shows the tree structure for major equipment failure with the conditional probabilities of contamination for several paths through the tree computed using the Bernoulli model. The complete tree structure with all of the conditional probabilities of contamination is given in Appendix B.

3.5.3 Event Probabilities

We have already assessed the probability of contamination associated with each path through the tree diagram for major equipment failure. The next step is to determine the relative likelihood of the paths. A typical assessment required is the following: Suppose midcourse corrections are accomplished as planned and Earth injection is within the nominal cone

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*It can be shown that the probability computed from the Bernoulli model will always be equal to or greater than the probability that would be computed from an equivalent model that assumes some degree of dependence.

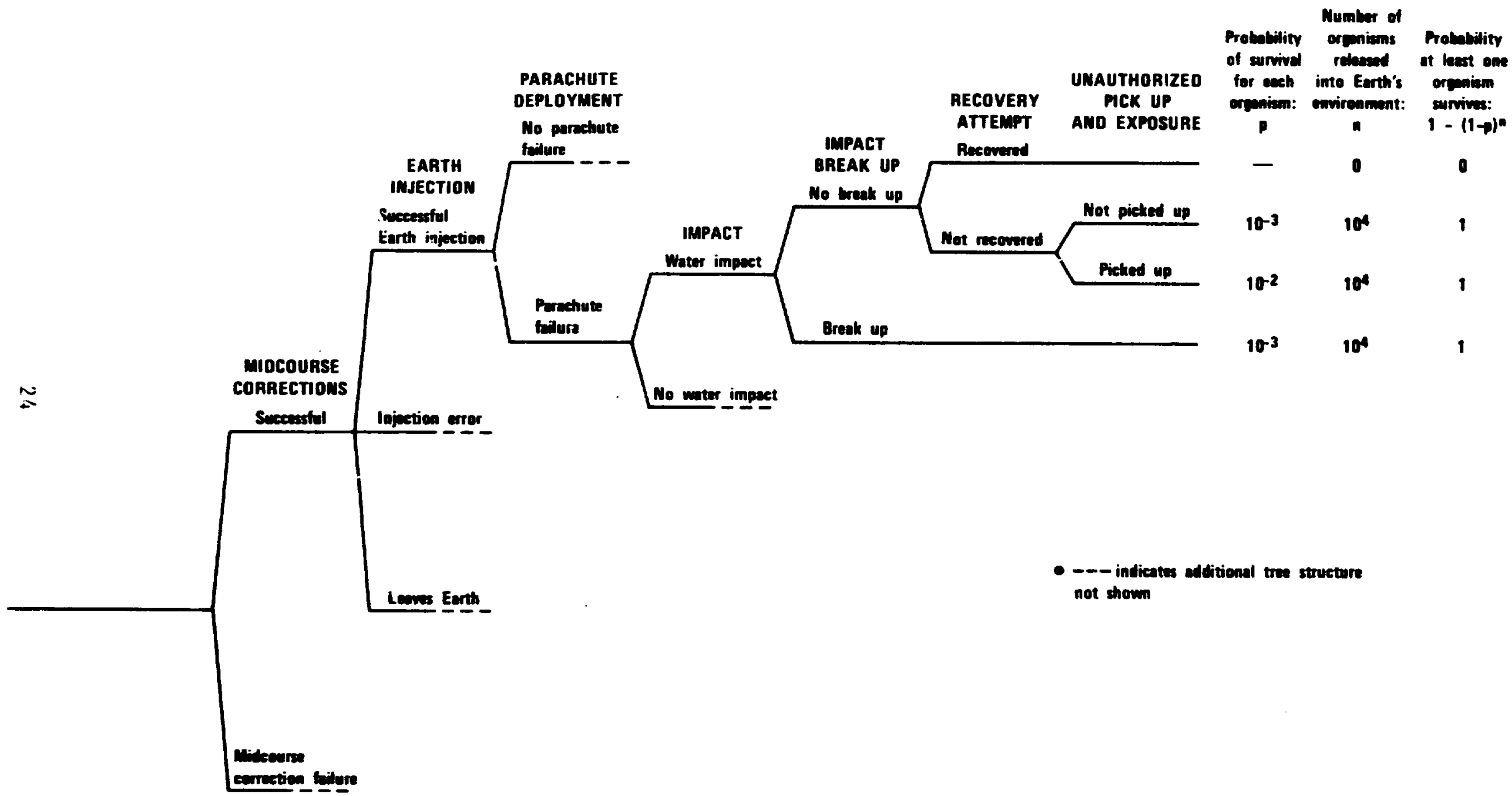


FIGURE 3.7 TREE DIAGRAM WITH CONDITIONAL PROBABILITIES OF SURVIVAL

of entry, what is the probability that the parachute will fail? Naturally, the answer to such a question requires that details of the mission design be specified. The reliability of the parachute system depends, for example, on specific details of the Earth-entry trajectory, including the velocity and altitude at the time of parachute deployment, as well as details of the parachute and deployment systems, including the extent to which redundancy is used to improve reliability.

The authors worked with various individuals at JPL to specify the details of the reference mission and to estimate reasonable probabilities for each of the outcomes of each of the events shown as branches in the tree structure. The assumptions made and probabilities agreed upon are summarized in Appendix B. Figure 3.8 shows some of these probabilities. The estimated probabilities for the outcomes for each of the events are noted under the corresponding branches in the tree. A tree structure with event probabilities represented in this way is called a probability tree.

The event probabilities shown under the branches are conditioned on the paths leading to the branches. For example, the probability under the branch labeled IMPACT BREAKUP is 0.3. This means that the assessed probability that the capsule and sample container will break up on impact is 0.3 assuming successful midcourse corrections and nominal Earth injection with parachute failure followed by water impact. Any changes in these assumptions would result in assignment of a different probability of impact breakup. For example, successful Earth injection followed by parachute failure followed by impact with a hard (nonliquid) surface (a sequence not represented in Figure 3.8) is assessed to have probability of 0.99 of impact breakup.

3.5.4 Computation of the Probability of Back-Contamination

The probability tree provides a graphical aid for combining event probabilities with conditional probabilities to obtain the overall probability of back-contamination. The method of computation uses what is commonly called a "tree roll-back procedure," which is based on the expansion principle of probability theory: The conditional probability of back-contamination associated with any node in the tree is found by multiplying the probability of each branch emanating from that node times the conditional contamination probability associated with the subseqent node on that branch and then adding the products for all branches leading from that node. Using this rule, the conditional contamination probability associated with each node in the tree can be computed starting first with the right-most nodes and using the results from these calculations to work back through the tree.

Appendix B reports the detailed results of applying the roll-back procedure to the probability tree; Figure 3.9 summarizes some of these results. The reader may verify that the conditional contamination probabilities, shown in boxes under nodes in the tree, equal the sum of the products of the branch probabilities times the conditional contamination probabilities of subsequent nodes.

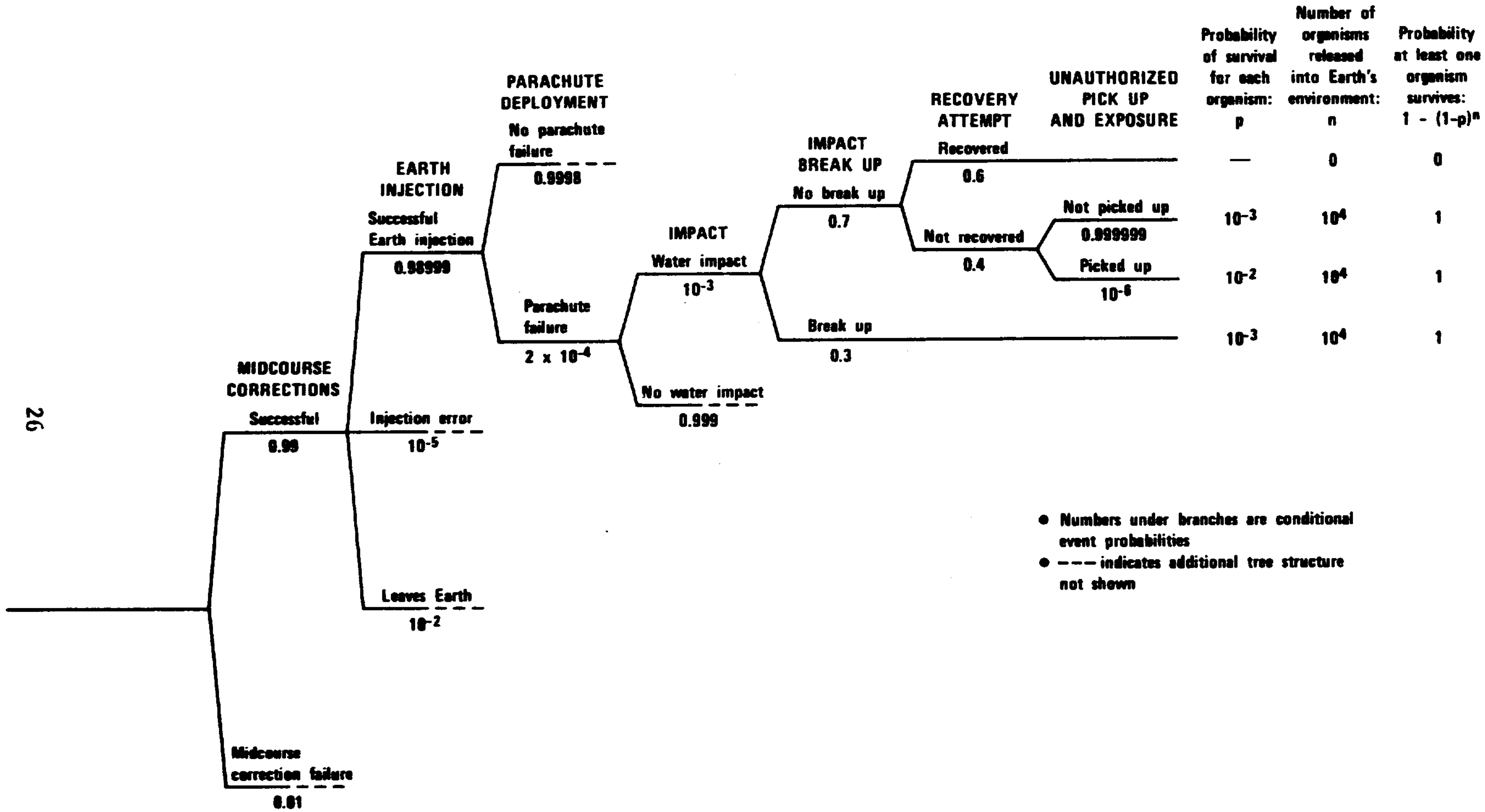


FIGURE 3.8 PROBABILITY TREE FOR MAJOR EQUIPMENT FAILURE

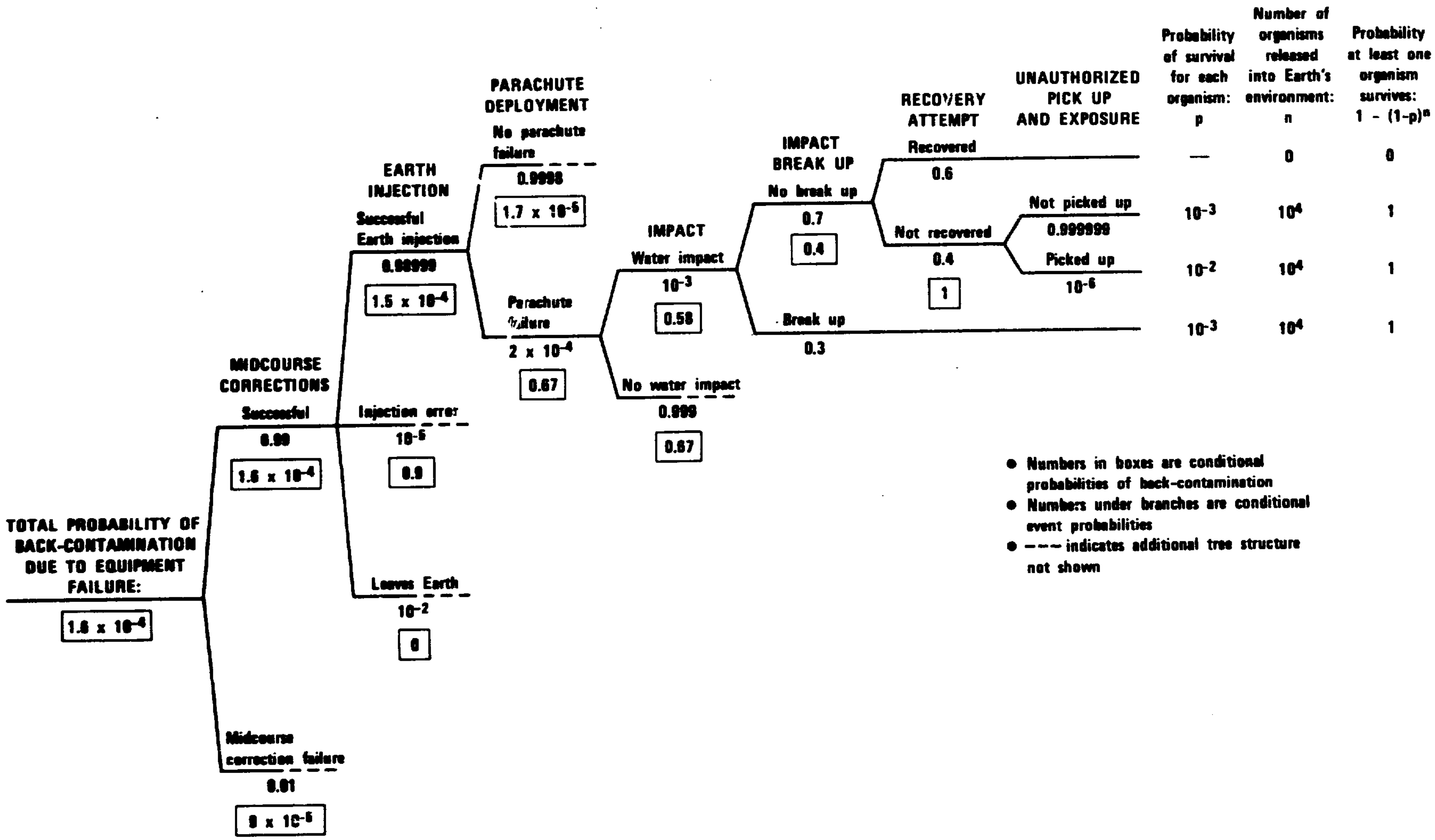


FIGURE 3.9 PROBABILITY TREE WITH ROLL-BACK RESULTS

Each of the conditional contamination probabilities is the probability of back-contamination, given that the events leading up to that node have occurred. In particular, the number in the box under the leftmost node at the trunk of the tree, 1.6×10^{-4}, is the overall (prior) probability of contamination for the risk category major equipment failure. The conditional probabilities in the boxes under the other nodes in the tree show how the probability of contamination would change, given the occurrence of various events. For example, the box under the node "impact" leading from the branch "parachute failure" contains the number 0.67. This indicates that if the mission proceeds in such a way that midcourse corrections are successful, Earth injection is successful, and then the parachute system fails, at the instant just prior to impact the probability of contamination is 0.67, or 2 chances out of 3.

3.5.6 Identifying Major Sources of Risk

The contribution of the risks associated with any node in the probability tree to the total probability of contamination can be obtained by multiplying the conditional probability at that node by the product of the probabilities along the path leading to the node. Probabilities obtained in this way are shown in the ovals in Figure 3.10. The results show that the basic risk elements in the category of major equipment failure contribute to the probability of contamination as follows:

Table 3.1

BASIC RISK ELEMENT PROBABILITIES

Risk Element	Contributed Probability of Back Contamination
Midcourse failure	9×10^{-7}
Earth injection	9×10^{-6}
Parachute failure	1.3×10^{-4}
Snatch failure	1.7×10^{-5}
Transportation accident	2.9×10^{-6}
Total	1.6×10^{-4}

Of the total 1.6×10^{-4} probability, 1.3×10^{-4} is due to sequences of events involving parachute failure. Thus, parachute failure is the single most important risk element in the category of major equipment failure. This contribution is due to the assessed probability of 2×10^{-4} of failure of the parachute system and the fact that contamination follows

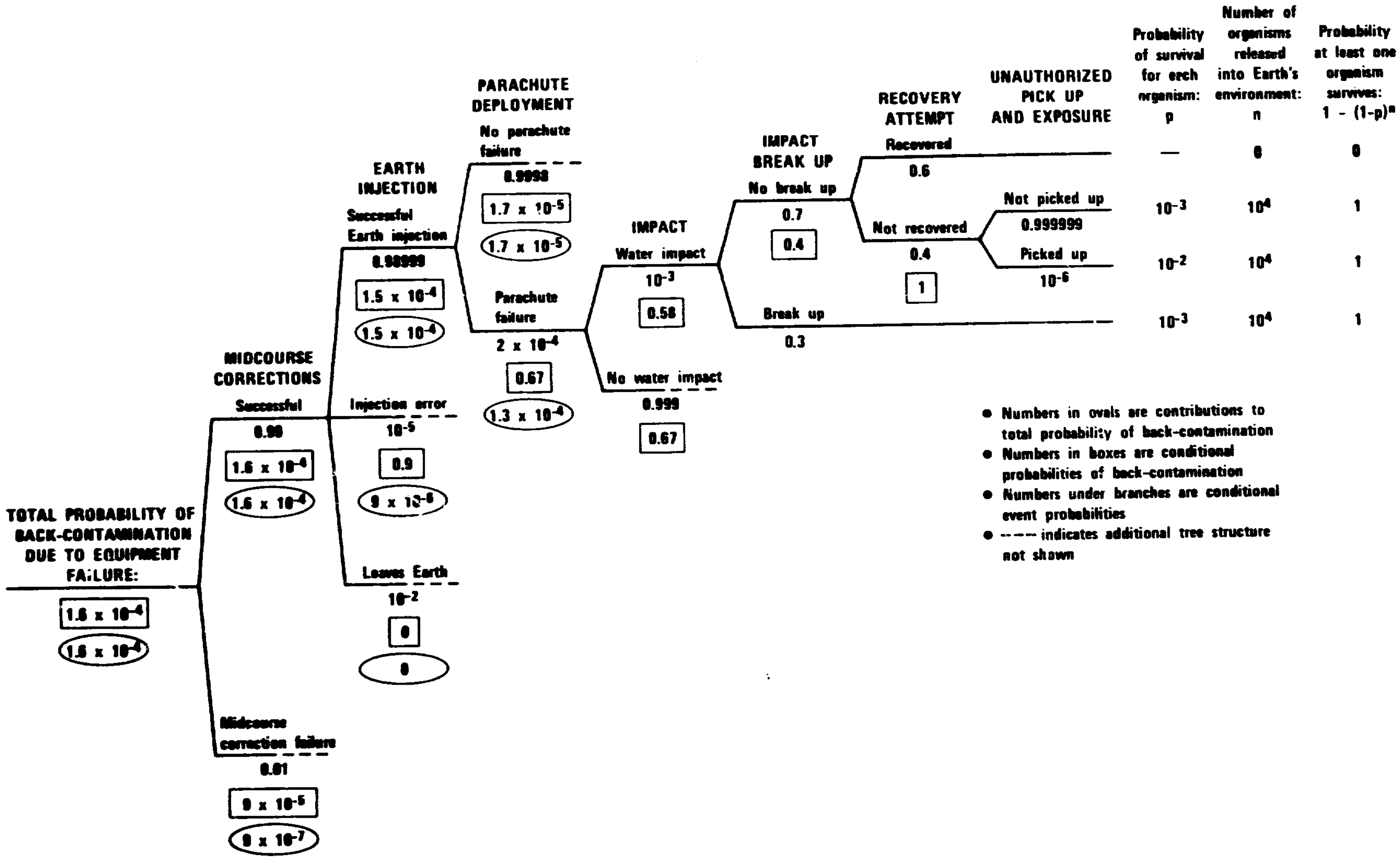


FIGURE 3.10 PROBABILITY TREE WITH ROLL-BACK RESULTS AND RISK CONTRIBUTIONS

parachute failure with a probability of 0.67. As described in Appendix B, the probability 2×10^{-4} of parachute failure is based on an assumption of two redundant parachute systems.

3.6 Leakage

This section describes the analysis of the probability of back-contamination due to leakage of one or more of the reference mission's biological seals. As described previously, the reference mission relies on triple seals to contain Martian organisms: a sample canister seal, a sample container seal, and a sample compartment seal. Thus, leakage of organisms from the sample requires failure of not one but three biological seals.

The risk of contamination through leakage, however, is not limited to leakage of organisms from the sample. Both the interior of the sample compartment and the interior of the sample container may be contaminated with Martian organisms. Therefore, in addition to considering the risk of leakage of organisms from the sample, the analysis also considers the risk that seal failure may lead to release of viable organisms that contaminate the interior of the sample compartment and sample container.

The nominal assumptions for the numbers and locations of Martian organisms were depicted in Figure 3.1. The assumed total number of Martian organisms in the sample is 10^4. It is assumed that the interior of the sample container is contaminated with an additional 100 organisms and that the sample compartment becomes contaminated during rendezvous with an additional 10 organisms. Appendix A contains a discussion of considerations that led to these assumptions. In Section 4.3, the sensitivity of analysis results to the assumptions is checked.

In Figure 3.2, two risk elements in the category of leakage are shown: The risk of leakage during heliocentric transfer of the Earth-return vehicle and the risk of leakage during entry of the Earth-entry capsule. For an organism leaked during heliocentric transfer to cause contamination, it not only must survive atmospheric entry, it must also survive ultraviolet radiation during transfer and be captured by Earth. Thus, organisms leaked during heliocentric transfer are less likely to result in back-contamination than organisms leaked during atmospheric entry. If a faulty seal results in leakage during heliocentric transfer, additional leakage during Earth entry is, of course, highly likely; however, the pressure difference during entry will make particle escape more difficult.

Since there are three sources of leakage (sample compartment, sample container, and sample canister) and two mission phases during which leakage may occur (heliocentric transfer and Earth entry), there are six leakage modes to consider. With the exception of canister leakage during heliocentric transfer and compartment leakage during heliocentric transfer, each of the leakage modes is assumed to result in the release of 1% of the exposed organisms. In the other two cases, 10% of the organisms within the sample are assumed ejected since the pressure difference under these failure modes will favor leakage.

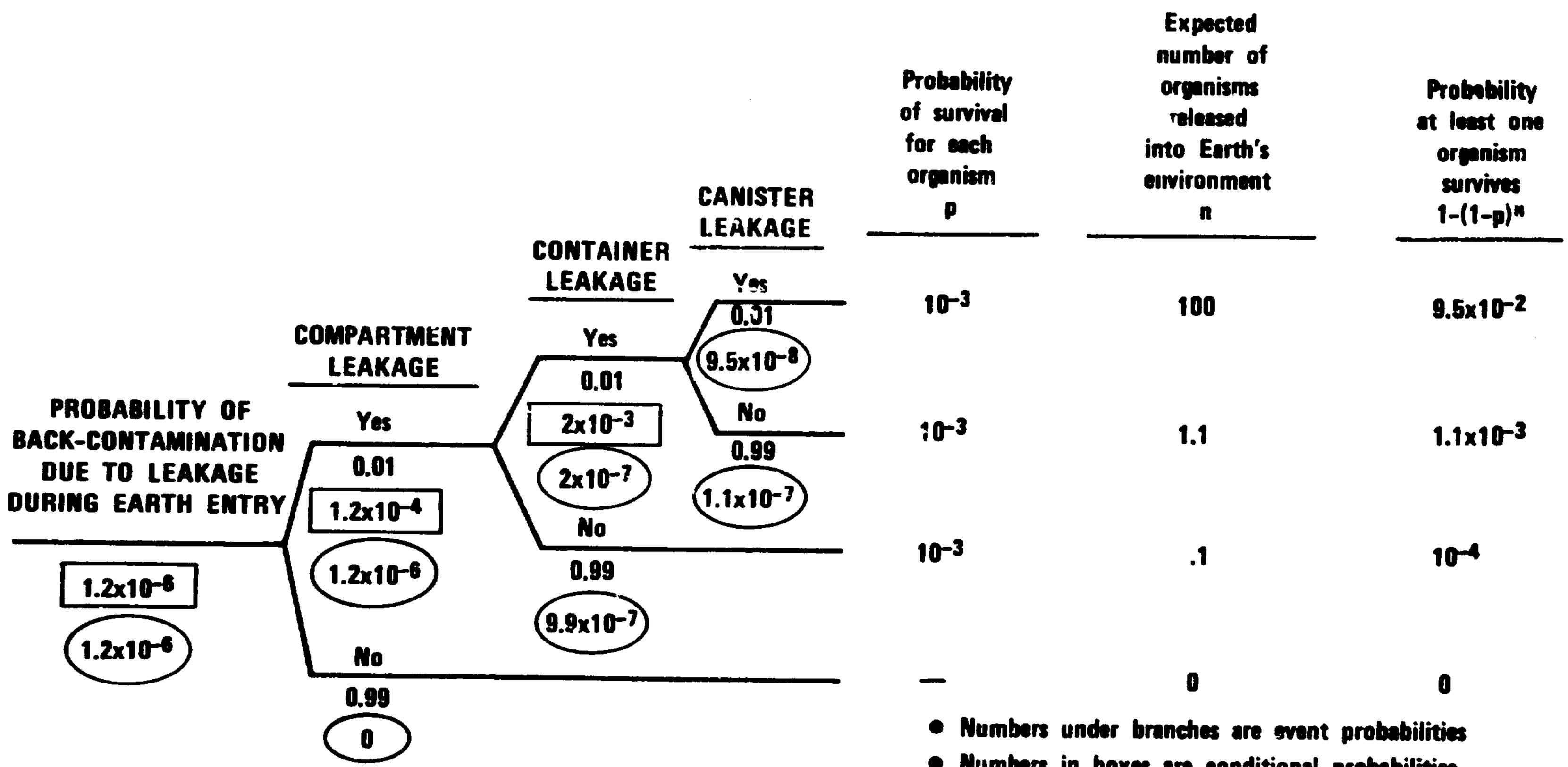
Figure 3.11 shows the probability tree constructed for analyzing the probability of back-contamination due to the risk of leakage during Earth entry. A similar tree for leakage during heliocentric transfer is given in Appendix C. The conditional probabilities of back-contamination associated with the various paths through the tree are computed using the Bernoulli model as was done for the risk category of major equipment failure. Notice that for each leakage mode, the number of exposed organisms is small compared to the reciprocal of the assumed probability of survival per organism, 10^{-2}. In this case the Sagan-Coleman approximation applies -- the probability that at least one organism survives is very nearly the product of the number of organisms released and the probability of survival per organism.

The probabilities under the branches of the tree in Figure 3.11 are the probabilities assessed for the leakage events. The failure probability of the seal on the sample compartment is assumed to be 1 chance in 100. If the sample compartment seal fails, the sample container seal is assumed to fail with probability 1 in 100. Similarly, failure of both the compartment and container seals will be followed by failure of a canister seal with probability 1 in 100. An explanation for these assumptions is given in Appendix C.

Conditional probabilities of contamination obtained using the rollback procedure are shown in the boxes under the nodes of the tree. The total probability of contamination shown in the box under the initial node is 1.3×10^{-6}. Table 3.2 summarizes the contributions from the various risk elements. Also included in the table are the results on the analysis of heliocentric leakage. One may observe from these numbers that the largest component of the risk during Earth entry is due to the risk of compartment leakage. Leakage during heliocentric transfer contributes an insignificant risk compared to leakage during Earth entry.

3.7 Surface Contaminants

This section summarizes the analysis used to obtain the contribution to the probability of back-contamination due to organisms that may be located on the exterior of the Earth-return vehicle. Because the mission design calls for a Mars-orbit rendezvous, the return vehicle does not come into direct contact with either the Martian surface or atmosphere. However, organisms may be transferred to the return vehicle during the docking maneuver with the Mars-ascent vehicle.



- Numbers under branches are event probabilities
- Numbers in boxes are conditional probabilities of back-contamination
- Numbers in ovals are contributions to total probability of back-contamination

FIGURE 3.11 PROBABILITY TREE FOR LEAKAGE DURING EARTH ENTRY

Table 3.2

LEAKAGE RISK ELEMENT PROBABILITIES

Risk Element	Probability of Back-Contamination
Organisms leaked during heliocentric transfer--	
Compartment leakage	2.7×10^{-10}
Container leakage	1.7×10^{-10}
Canister leakage	6.3×10^{-11}
Organisms leaked during Earth entry--	
Compartment leakage	1.2×10^{-6}
Container leakage	2.0×10^{-7}
Canister leakage	1.1×10^{-7}

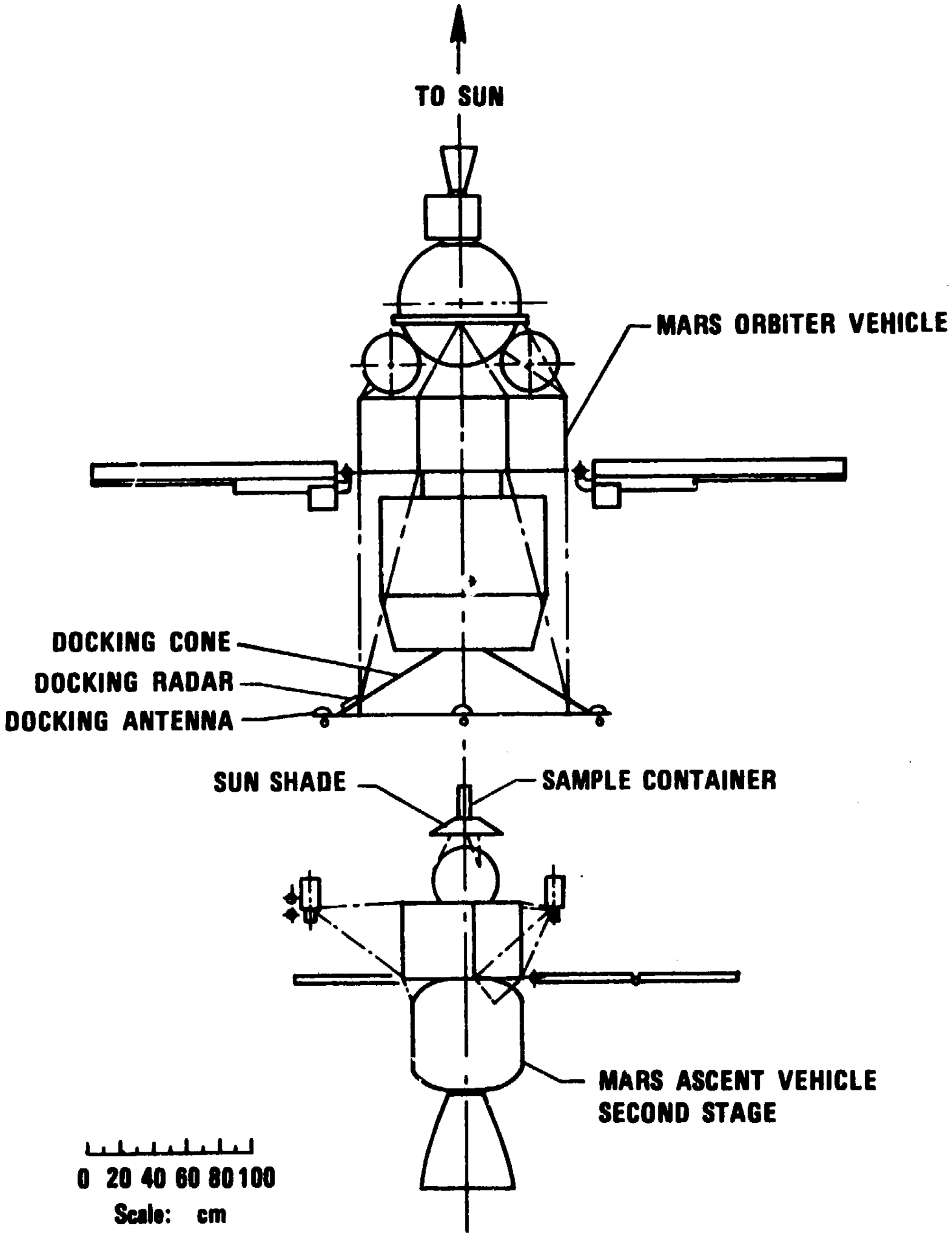
3.7.1 Number of Organisms Transferred to the Earth-Return Vehicle

As shown in Figure 3.1, the expected number of organisms assumed to be transferred to the Earth-return vehicle during rendezvous is 0.02. This number depends critically on docking geometry. Figure 3.12 shows the orientation assumed for the ascent vehicle and the orbit vehicle just before docking. The orbit vehicle will approach the ascent vehicle and orient itself so as to accept transfer of the sample container. The two vehicles may keep station in this orientation for several days. Then the orbit vehicle will move forward and latch itself to the ascent vehicle. The sample container will be transferred to the sample compartment inside the Earth-entry capsule. Finally, the orbit vehicle and Mars-ascent vehicle will disengage with the docking cone remaining attached to the Mars-ascent vehicle.

Transfer of surface organisms can happen when particles are dislodged from the ascent vehicle by the slight bump that may occur when the ascent vehicle and orbit vehicle make contact. Most of the particle transfer that occurs in this way will depend on a line-of-sight path to the Earth-return vehicle. In this respect, the docking cone functions as a bio-shield.

Transfer may also occur during the station-keeping phase. There will be no line of sight then, but particle transfer may result from the interplay of solar radiation and electrostatic forces.

With this geometry, and assuming worse case conditions, the expected number of organisms transferred was calculated to be 0.02. The detailed assumptions behind this estimate appear in Appendix C.



*Reproduced from reference 19.

FIGURE 3.12 DOCKING GEOMETRY*

3.7.2 Paths Followed by Surface Contaminants

Organisms located on the exterior of the Earth-return vehicle may enter the Earth's environment either on the surface of the Earth-entry capsule or because they are dislodged prior to capsule recovery and follow a trajectory that results in Earth capture. Figure 3.13 summarizes the assumptions made concerning the expected fraction of surface organisms that would follow various paths that may or may not lead to contamination. Since the numbers of organisms are less than one, these may be interpreted as probabilities that a given organism would follow each of the possible paths.

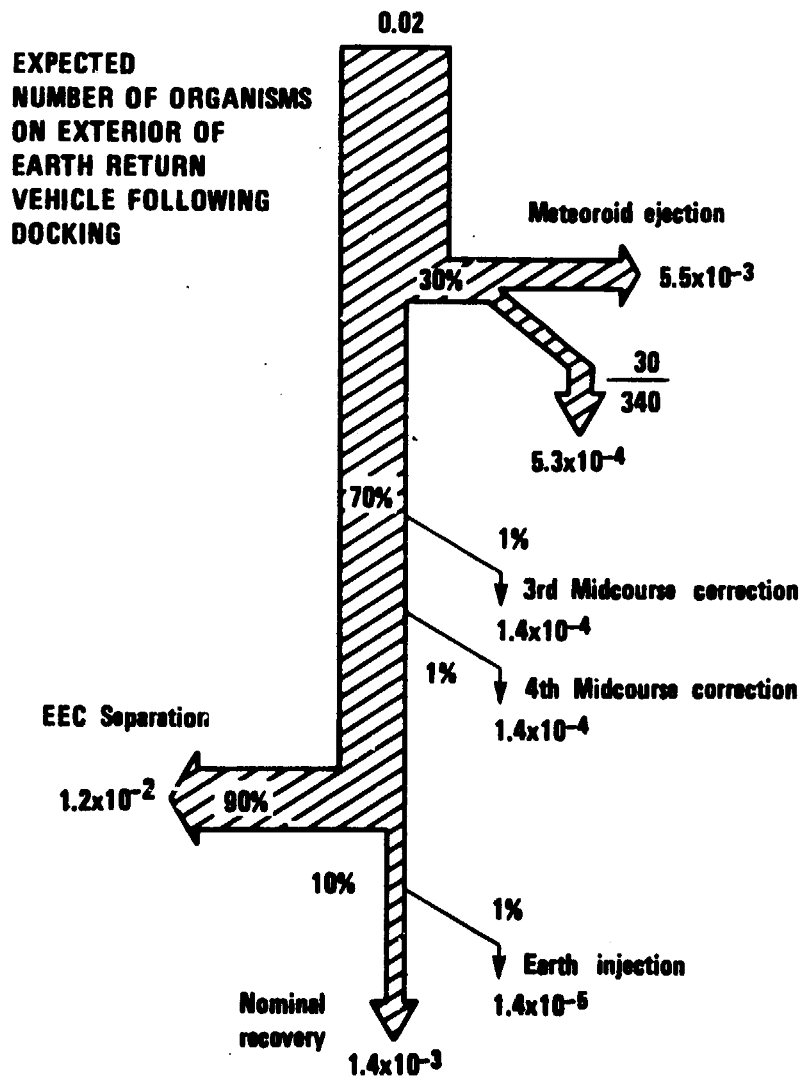


FIGURE 3.13 ASSUMED PATHS FOR MARTIAN ORGANISMS ON THE EARTH-RETURN VEHICLE EXTERIOR

As indicated by the figure, 30 percent of the surface organisms are assumed to be ejected by vibrations caused by micrometeoroid impact. The ejection is assumed to be roughly uniform over time. Those organisms that are ejected during the last 30 days of the 340-day return trip are assumed accessible to possible Earth capture. Organisms dislodged by the last two midcourse corrections are also assumed to be available for Earth capture. Of the remaining organisms, 1 percent are assumed dislodged during each of the last two midcourse maneuvers. Of the organisms that are not dislodged, 10 percent are assumed to be located on the Earth-entry capsule; all others remain on the discarded return vehicle. Of the organisms on the entry capsule, 1 percent are assumed to be dislodged by Earth injection.

3.7.3 Summary of Results--Surface Contaminants

For a dislodged organism to cause contamination, it must survive heliocentric transfer, be captured by Earth, and survive once it enters Earth's atmosphere. An organism that remains on the entry capsule may cause contamination only if it survives heliocentric transfer and capsule heatup during entry. The tree structures that represent these sequences of events are given in Appendix C together with the results of the tree roll-back. The table below summarizes the contamination probabilities contributed by each of the risk elements:

Table 3.3

SURFACE ORGANISM RISK ELEMENT PROBABILITIES

Risk Element	Probability of Back-Contamination
Organisms dislodged by	
Third midcourse correction	4.2×10^{-12}
Fourth midcourse correction	2.1×10^{-11}
Micrometeoroid impact	2.1×10^{-10}
Earth injection	1.4×10^{-9}
Organisms on capsule exterior at Earth entry	1.4×10^{-8}
Total probability due to surface organisms:	1.6×10^{-8}

3.8 Summary of Results of the Analysis of the Reference Mission

Table 3.4 summarizes the probabilities of back-contamination for each of the three risk categories analyzed. The total probability is due almost entirely to the risk of major equipment failure. Most of the

Table 3.4

SUMMARY OF BACK-CONTAMINATION PROBABILITIES
FOR REFERENCE MISSION

Risk Category	Probability of Back-Contamination	Major Source of Risk
Major equipment failure	1.6×10^{-4}	Parachute failure
Leakage	1.2×10^{-6}	Leakage of sample compartment seal during Earth Entry
Surface contaminants	1.6×10^{-8}	Organisms located on Earth Entry capsule at time of Earth Entry
Total	1.6×10^{-4}	

probability of back-contamination associated with major equipment failure is due to the risk of parachute failure and the fact that parachute failure leads to contamination with rather high probability. The risk of contamination due to leakage is two orders of magnitude lower, and the probability of contamination due to surface contaminants is smaller still. In the category of leakage, the major source of risk is leakage of the compartment seal during Earth entry. In the case of surface contaminants, the major source of risk is organisms that remain on the Earth-entry capsule through Earth entry. Surface organisms dislodged by vibration are of little importance.

Note that the extension of the analysis to include a model for the survival of released Martian organisms may indicate that the risk of contamination due to major equipment failure is less important relative to the other two categories than is indicated here. As discussed in Section 3.5.2, the conservative assumption that each Martian organism lives or dies with independent probability has the effect of virtually guaranteeing survival of at least one organism if a large enough number of organisms are released. Since major equipment failure is the only risk category that may result in a large number of organisms being released, more detailed modeling of the generic capability of Martian organisms to survive on Earth will affect the risk assessment for major equipment failure more severely than the other two categories. If, for example, a model for survival such as that shown in Figure 3.6 were used instead of the independence assumption, the assessment for the probability of back-contamination due to major equipment failure would be reduced by about two orders of magnitude. The assessments for the other two categories would be insignificantly affected.

Since the major risk sources identified occur during the Earth-entry phase of the mission, it may be useful to consider alternative ways of retrieving the sample that bypass direct Earth entry of the capsule. For example, Appendix E discusses orbital recovery, in which the capsule is retrieved in Earth orbit, sealed in a protective box, and then returned with the shuttle for analysis in an Earth-based receiving laboratory. The preliminary analysis in Appendix E shows that this approach has the potential for a significant reduction in the probability of back-contamination at a somewhat higher mission dollar cost.

The next chapter investigates the sensitivity of the results of this chapter to the detailed numerical assumptions made in the construction of the probability trees.

IV SENSITIVITY ANALYSIS OF THE REFERENCE MISSION

Many ad hoc assumptions were made in arriving at the probability of back-contamination for the reference mission of 1.6×10^{-4}.* Although the method of analysis -- probability theory and the principle of decomposition -- is perfectly general, the particular probability trees that were developed to model the reference mission embody many assumptions that could be relaxed through more detailed modeling.

For example, an assumption is made throughout the analysis that the sample canisters contain a total of 10^4 organisms. Instead, additional nodes and branches could be added to the tree structures to represent other possibilities. One branch could be added to indicate an outcome of the sampling that resulted in no organisms being contained in the samples, another to indicate an outcome in which only a very small number of viable organisms were obtained, and a third to represent a situation in which a very large number of organisms were obtained. Another mathematically equivalent approach would be to compute the probability of contamination for all possible numbers of organisms in the sample. A probability distribution for the number of organisms in the sample could then be developed, and the probability of contamination would be obtained by integrating the result over this distribution.

Clearly, the analysis could be improved in many such areas. Frequently, though, it is most efficient to construct a relatively simple probability tree model, as we have done here, before attempting to capture all of the available knowledge relevant to the problem with a more complicated model. This is because the simple model can be used as a basis for sensitivity studies that identify those aspects of the initial analysis whose refinement is most likely to influence analysis results. This chapter describes sensitivity studies conducted on the analysis of the reference mission and the implications of the results of these studies.

4.1 Individual and Joint Sensitivities

Two kinds of sensitivity studies were performed on the probability tree models developed for the reference mission: single variable sensitivities and cumulative sensitivities. In a single variable sensitivity analysis of a model, one of the inputs to the model is varied over a range of values while the other inputs are held constant. This determines the

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*Again the reader is reminded that this is the probability of "potential back-contamination," not the probability of "actual back-contamination." See Section 2.2 and the comment at the beginning of Chapter III.

sensitivity of the model outputs to that input. In a cumulative sensitivity analysis, two or more inputs are simultaneously varied by proportional amounts while observing the effect on the outputs.

For the analysis of the probability of back-contamination from the reference mission, the model consists of probability trees. The inputs to the model are the various assumptions that are either explicitly or implicitly embodied in the tree, such as the event probabilities noted under the tree branches and the numbers and locations of Martian organisms assumed for the computation of the conditional contamination probabilities at the ends of the tree. The outputs of the model are the probabilities of back-contamination produced by the roll-back procedure, in particular the overall probability of back-contamination associated with the initial node of the tree.

Thus, single variable sensitivities were obtained for the reference mission analysis by individually varying each assumption and recomputing the tree roll-back values. Cumulative sensitivities were obtained by simultaneously varying several assumptions. The following sections summarize the results. The work is organized by risk element category.

4.2 Major Equipment Failure

Figure 4.1 is a sensitivity result showing how the probability of contamination by major equipment failure depends on the number of organisms assumed in the sample. Specifically, the figure shows the probability of back-contamination plotted as a function of a factor by which the nominal assumption is multiplied. If the factor is unity, one has the original assumption of 10^4 organisms in the sample, which gives the previously obtained probability of contamination of 1.6×10^{-4}. If the assumed number of organisms is decreased by a factor of 0.1, to 10^3, then the probability of contamination drops slightly, to about 1×10^{-4}.

As illustrated by Figure 4.1, as long as there are 10^3 or more organisms in the sample, the probability of contamination is about 10^{-4}. If the number is dropped below 10^3, then the probability of contamination drops almost proportionally.

Figure 4.2 shows two more sensitivity results in the category of major equipment failure. One curve shows how the probability of contamination depends on the assumed probability of Earth capture of the capsule in the event of midcourse failure. Interestingly, it shows that the risk of back-contamination is rather insensitive to the Earth-capture probability. For the reference mission, the bias of the return trajectory away from Earth could be relaxed so that probability of Earth capture in the event of midcourse failure was increased by a factor of 100, to 10^{-2}; this would have an insignificant effect on the total probability of contamination from the mission.

The second curve in Figure 4.2 shows the sensitivity of the probability of back-contamination to the probability of parachute failure.

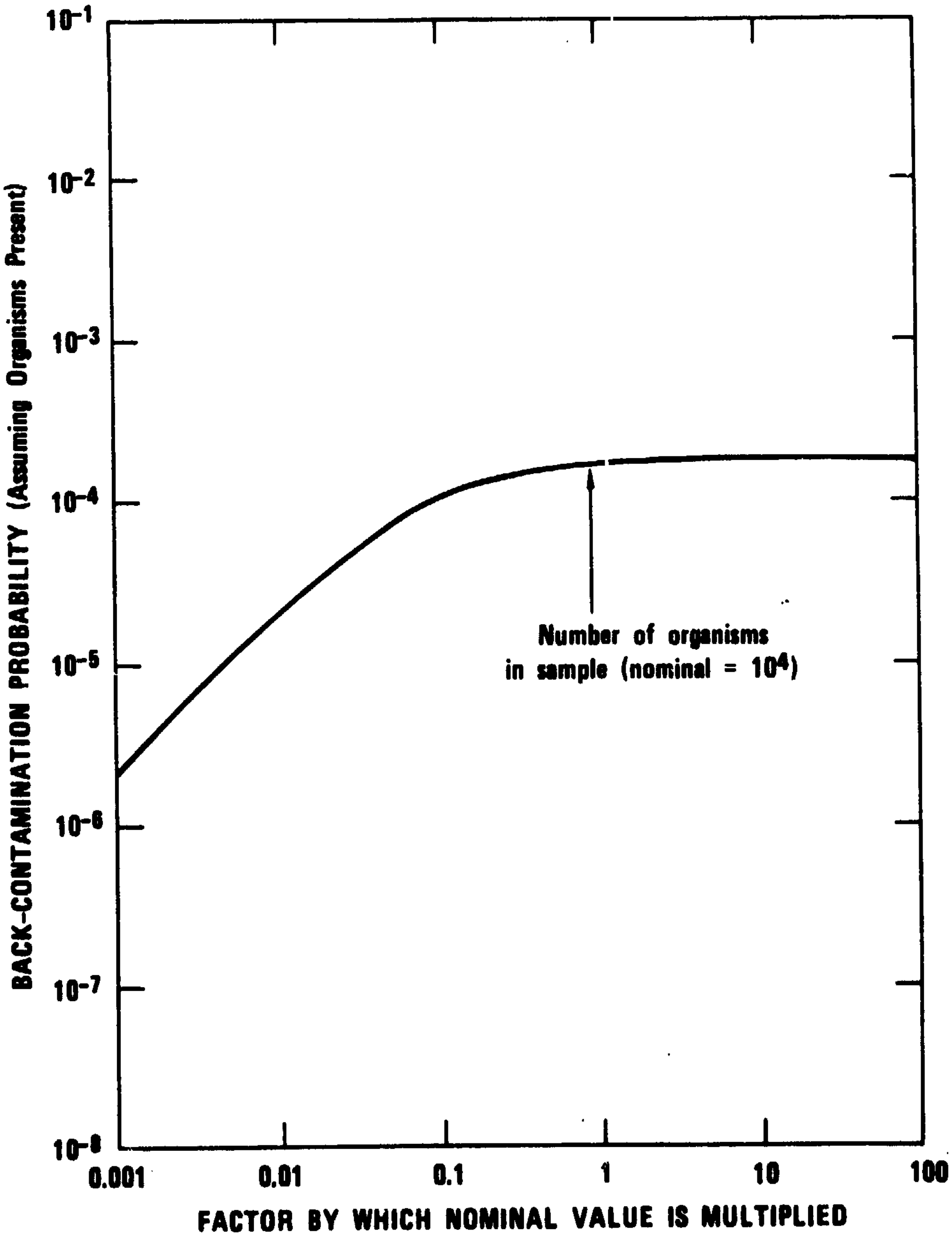

FIGURE 4.1 PROBABILITY OF BACK-CONTAMINATION SENSITIVITY TO NUMBER OF MARTIAN ORGANISMS IN THE SAMPLE

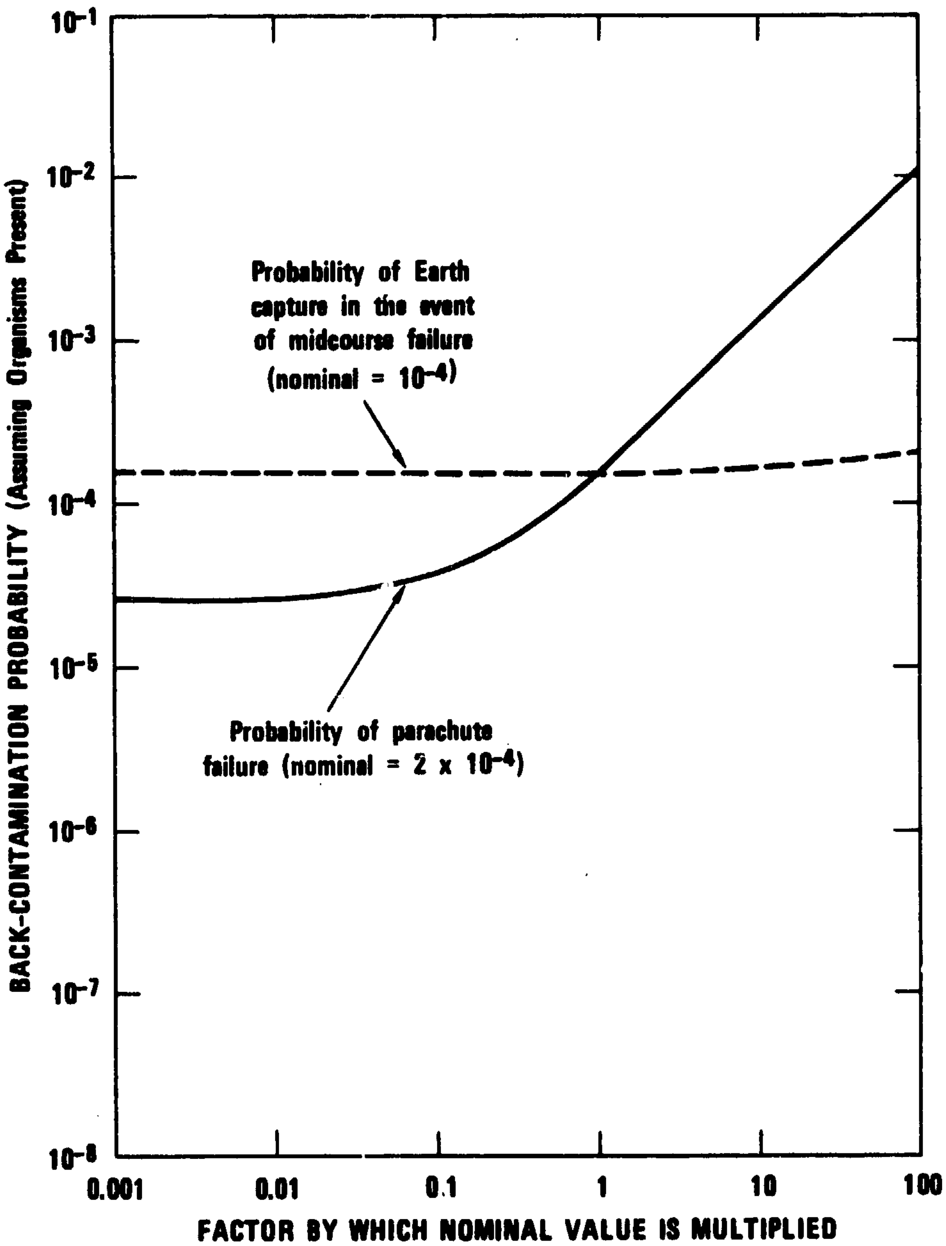

FIGURE 4.2 SENSITIVITIES TO PARACHUTE RELIABILITY AND PROBABILITY OF EARTH CAPTURE IN THE EVENT OF MIDCOURSE FAILURE

Parachute failure is the dominant risk element in the category of major equipment failure; even allowing for two redundant parachutes, the probability of parachute failure contributes 1.3×10^{-4} out of the total probability of 1.6×10^{-4}. As illustrated in Figure 4.2, if the probability of parachute failure is higher than assumed, the probability of contamination increases rapidly. On the other hand, the maximum reduction in the probability of contamination that can be obtained by improving the reliability of the parachute alone is less than one order of magnitude.

Because the parachute system contributes such a large proportion of the total back-contamination risk, little would be gained by decreasing the contribution of other risk elements. On the other hand, the overall contamination probability will be increased if one increases the risk from other risk elements to a level commensurate with the risk from parachute failure. Figure 4.3 illustrates this point with sensitivity results to the probability of missing the snatch and the probability that the capsule will be broken apart during the snatch attempt, perhaps by collision with the airplane attempting the snatch. Figure 4.4 shows the sensitivity to the chance of non-nominal Earth injection (which could be caused by the solid fueled rocket failing to burn completely). A drastic reduction in any of these probabilities does not materially reduce the overall probability of back-contamination; a large increase is eventually reflected in the overall probability.

Figure 4.5 shows the sensitivity of back-contamination probability to the probability that the capsule would fail to be recovered in the event of parachute failure. (The chances of recovering the capsule depend on the nature of the surface it hits -- water, land, etc. -- and on whether or not it breaks up on impact. Recovery of the capsule in the event it has broken up implies the recovery of the major part of the sample and the initiation of efforts to sterilize the area.) If recovery is assumed, the probability of contamination is reduced by about a factor of three from the nominal case.

Figure 4.6 shows the sensitivity of the probability of back-contamination to the probability of survival of a single organism. This calculation has been performed using the assumption of independence discussed in Section 3.5.2, which provides a very conservative estimate for the probability of contamination under a given method or sample release. The contamination probability is insensitive to increases in the survival probability assumed for an individual organism. This is because the independence assumption virtually guarantees contamination for most paths through the major equipment failure probability tree that result in sample release.

Figure 4.7 shows a series of cumulative sensitivities. Curve a, reproduced from Figure 4.2, shows the sensitivity of contamination probability to the probability of parachute failure. As the probability of parachute failure is reduced by about an order of magnitude, the effect on back-contamination risk levels off. At this point, the other risk elements begin to make major contributions, and reducing the chance

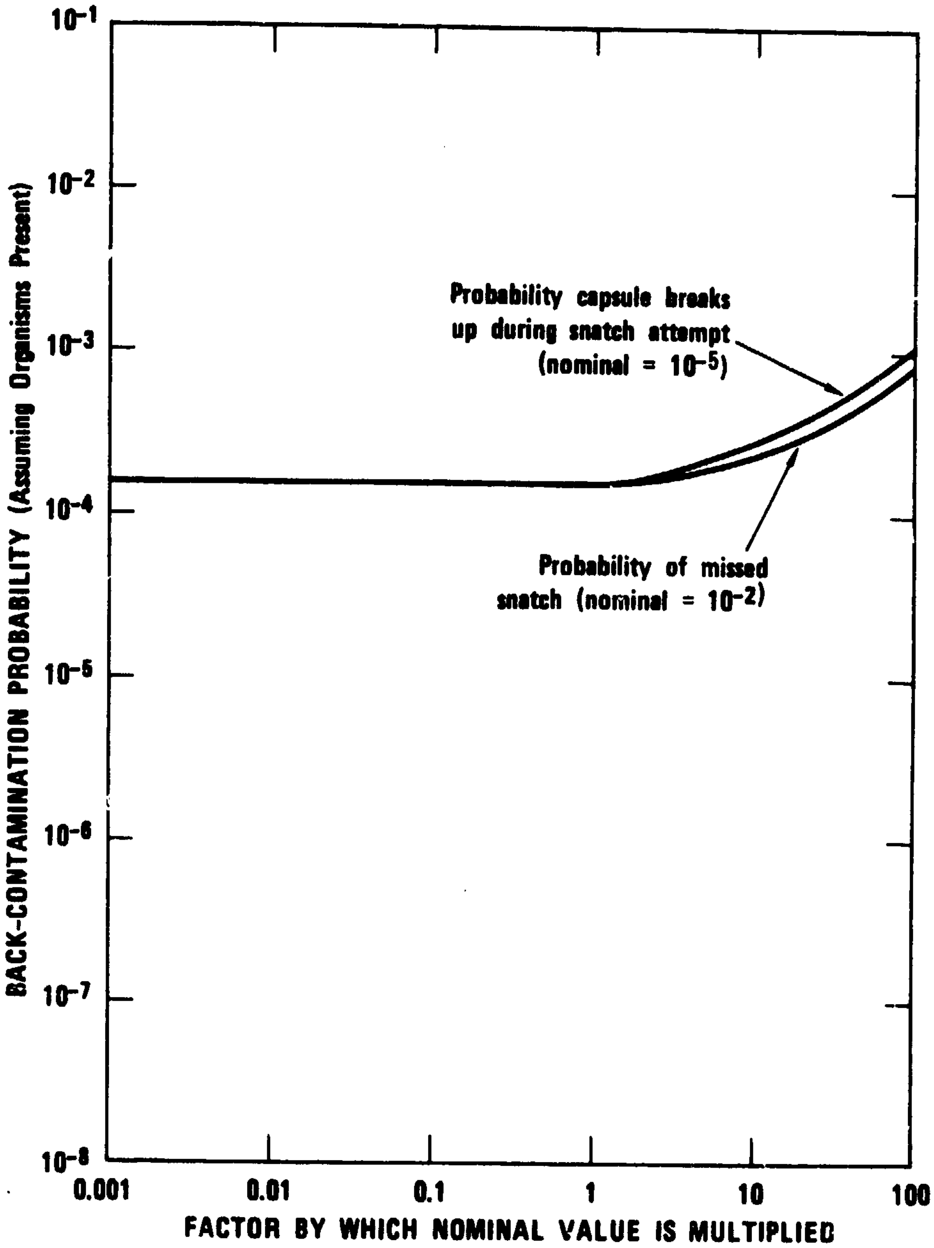

FIGURE 4.3 SENSITIVITIES TO SNATCH FAILURE PROBABILITIES

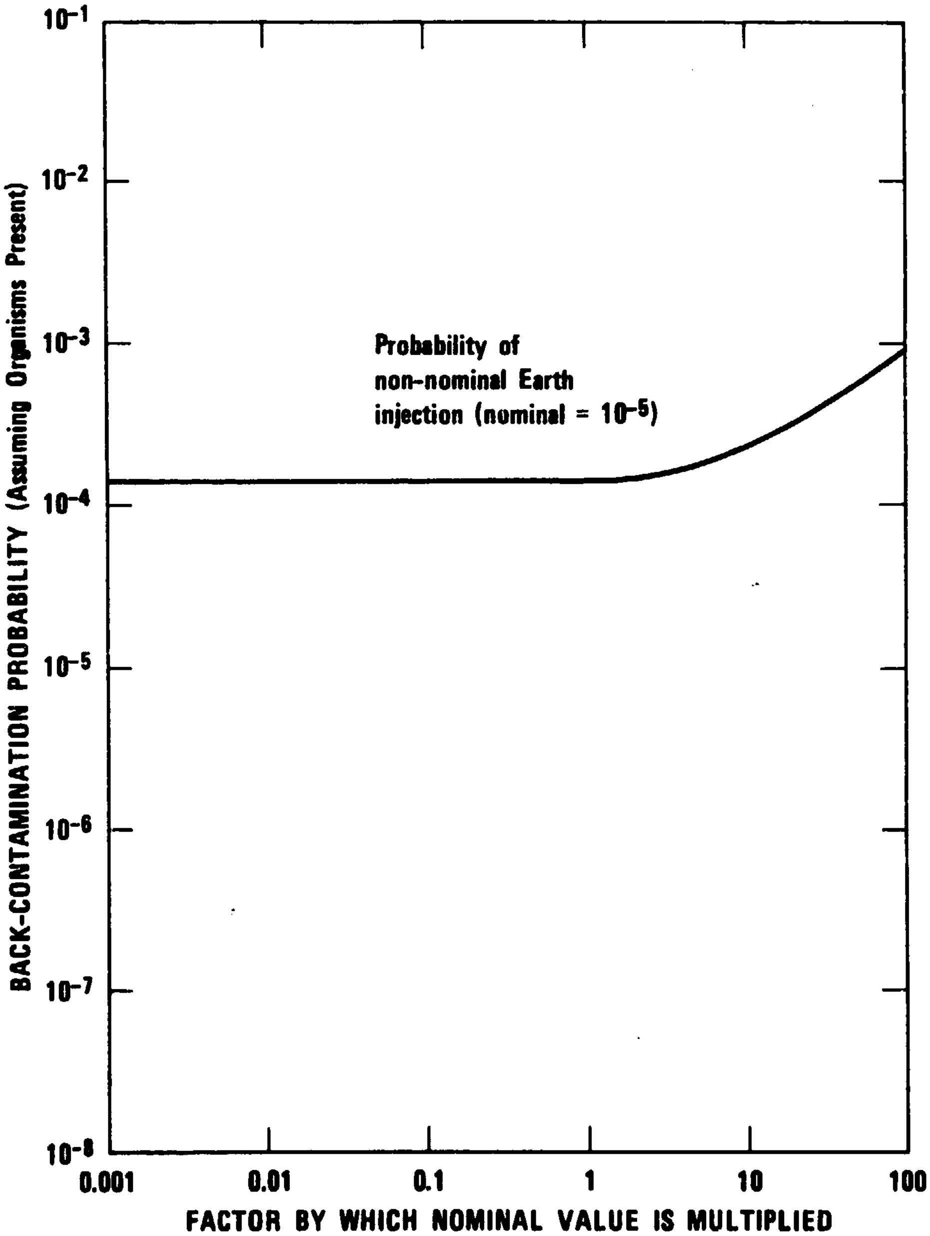

FIGURE 4.4 SENSITIVITY TO PROBABILITY OF NON-NOMINAL EARTH INJECTION

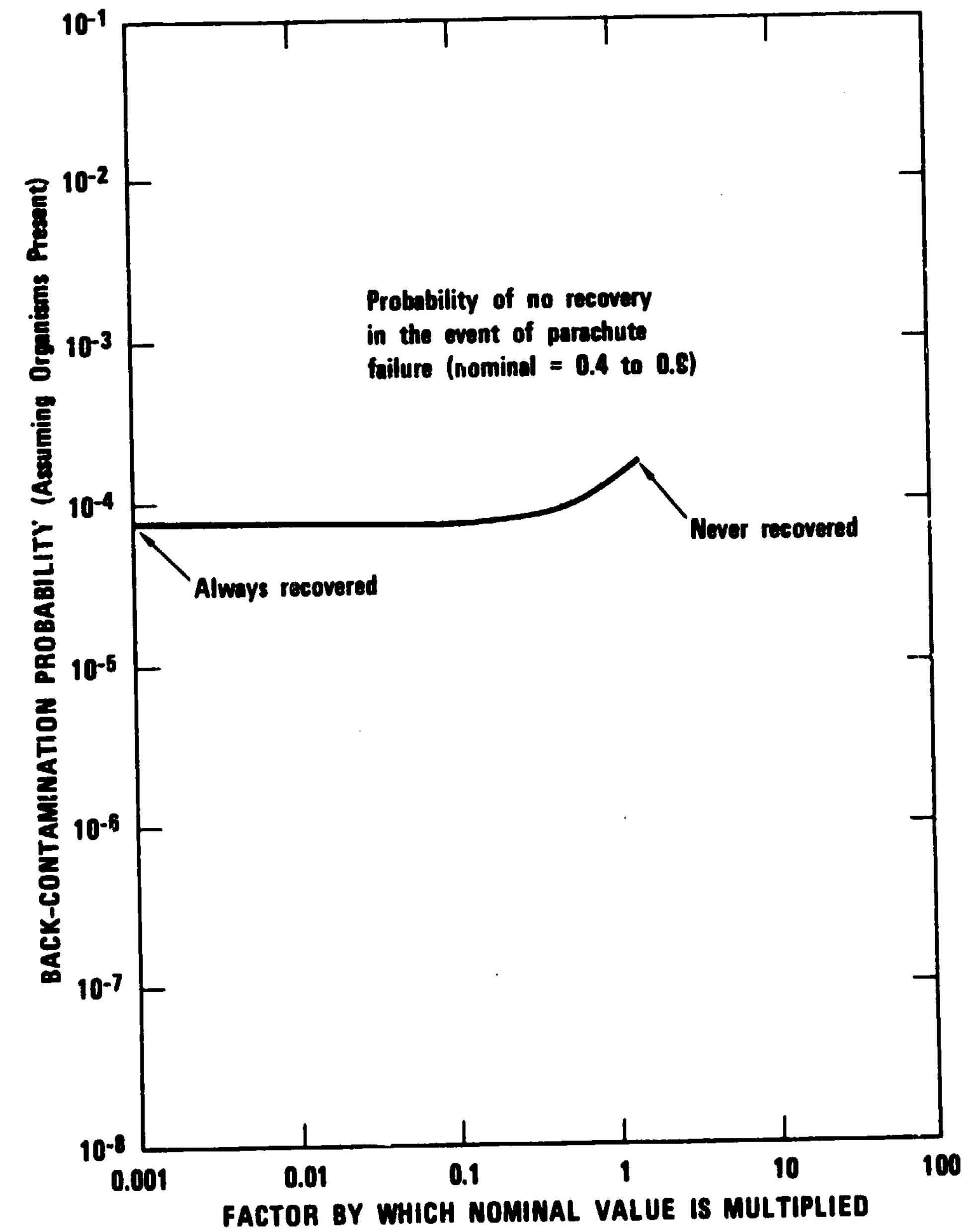

FIGURE 4.5 SENSITIVITY TO PROBABILITY OF NO RECOVERY IN THE EVENT OF PARACHUTE FAILURE

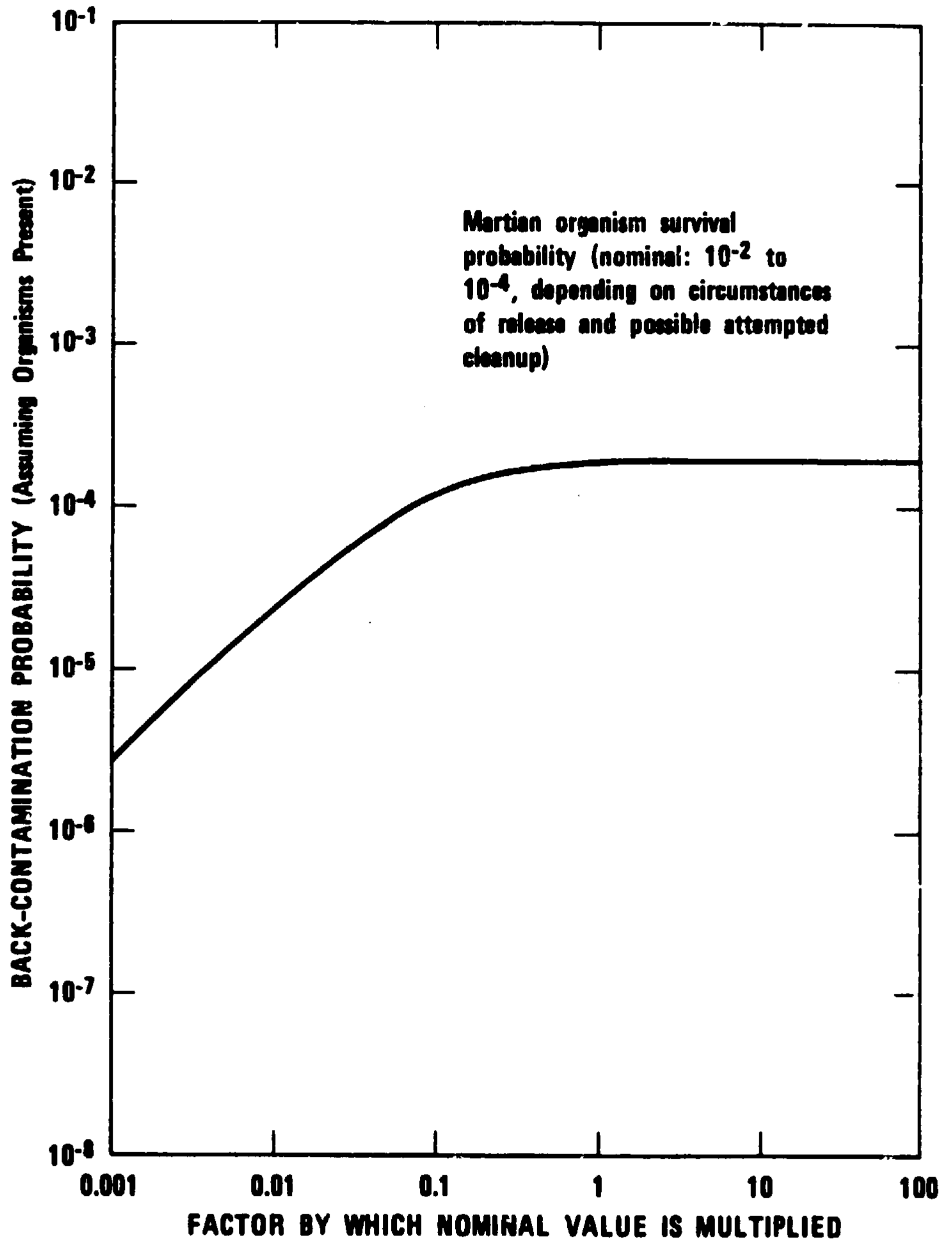

FIGURE 4.6 SENSITIVITY TO ASSUMED SURVIVAL PROBABILITY OF EACH MARTIAN ORGANISM

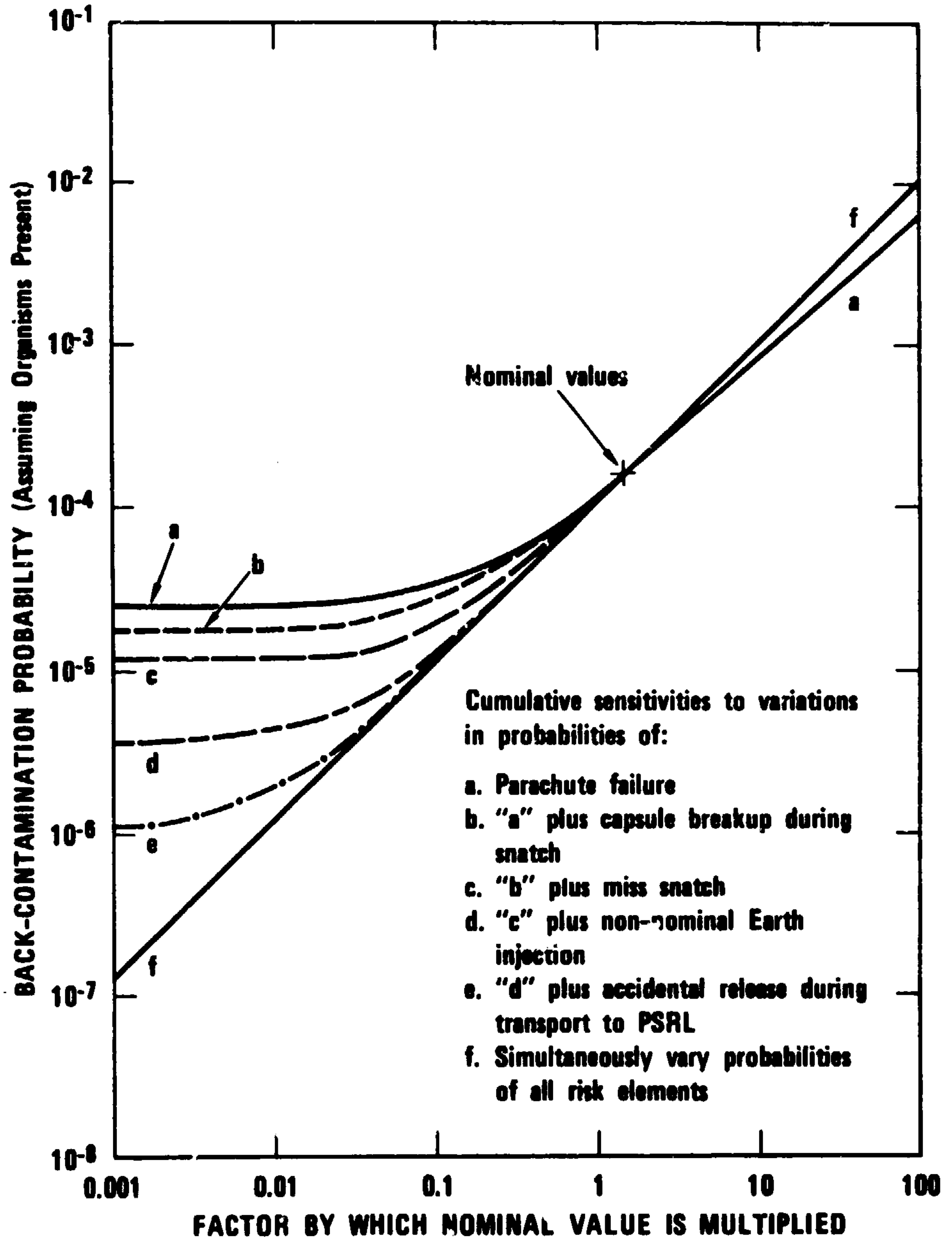

FIGURE 4.7 CUMULATIVE SENSITIVITY RESULTS

of parachute failure further has little effect on the overall contamination probability. Curve b represents the case where the two most individually sensitive reliabilities, the probabilities of parachute failure and capsule breakup during the snatch attempt, are simultaneously varied. If both of these probabilities can be lowered, the probability of back-contamination is reduced somewhat further. Curves c, d, e, and f represent the cases where additional risk elements are successively added to the sensitivity analysis. In order to achieve an overall contamination probability below 10^{-5}, one needs to improve at least four probabilities by at least an order of magnitude each.

4.3 Leakage

Figure 4.8 shows the sensitivity of the probability of contamination due to leakage to the number of Martian organisms assumed in various locations. Again the risk is rather insensitive to the number of organisms in the sample itself. On the other hand, the probability is sensitive to the number of organisms in the sample compartment. Thus, a mechanism for reducing the number of organisms that contaminate the sample compartment would be a way to reduce the back-contamination risk due to leakage for the reference mission.

Figure 4.9 shows several more sensitivity results in the category of leakage events. One curve shows the sensitivity of contamination to the reliability of the sample compartment seal while the other curve shows the sensitivity to the reliability of the sample canister seal.

4.4 Surface Contaminants

Figure 4.10 shows two sensitivity results for the category of contamination due to surface contaminants. The most sensitive assumption in this category is the number of organisms on the entry capsule at the time of atmospheric entry.

4.5 Conclusions

The sensitivity studies indicate the assumptions made in the analysis of the reference mission that most critically affect the probability of back-contamination. Many of the most sensitive parameters found in the sensitivity studies may, to a certain extent, be controlled by the design of the reference mission. Since the reliability of the parachute is the most sensitive single source of risk, we can conclude that risk may be reduced either by improving the reliability of the parachute system or by providing methods for sterilizing or incinerating the sample in the event of parachute failure. (Chapter V treats the latter case.) The other sensitive area for improvement has to do with leakage. The risk of back-contamination due to leakage can be reduced if the reliability of the seal on the sample compartment is improved or if the number of organisms in the sample compartment can be reduced--for example, by using a thin

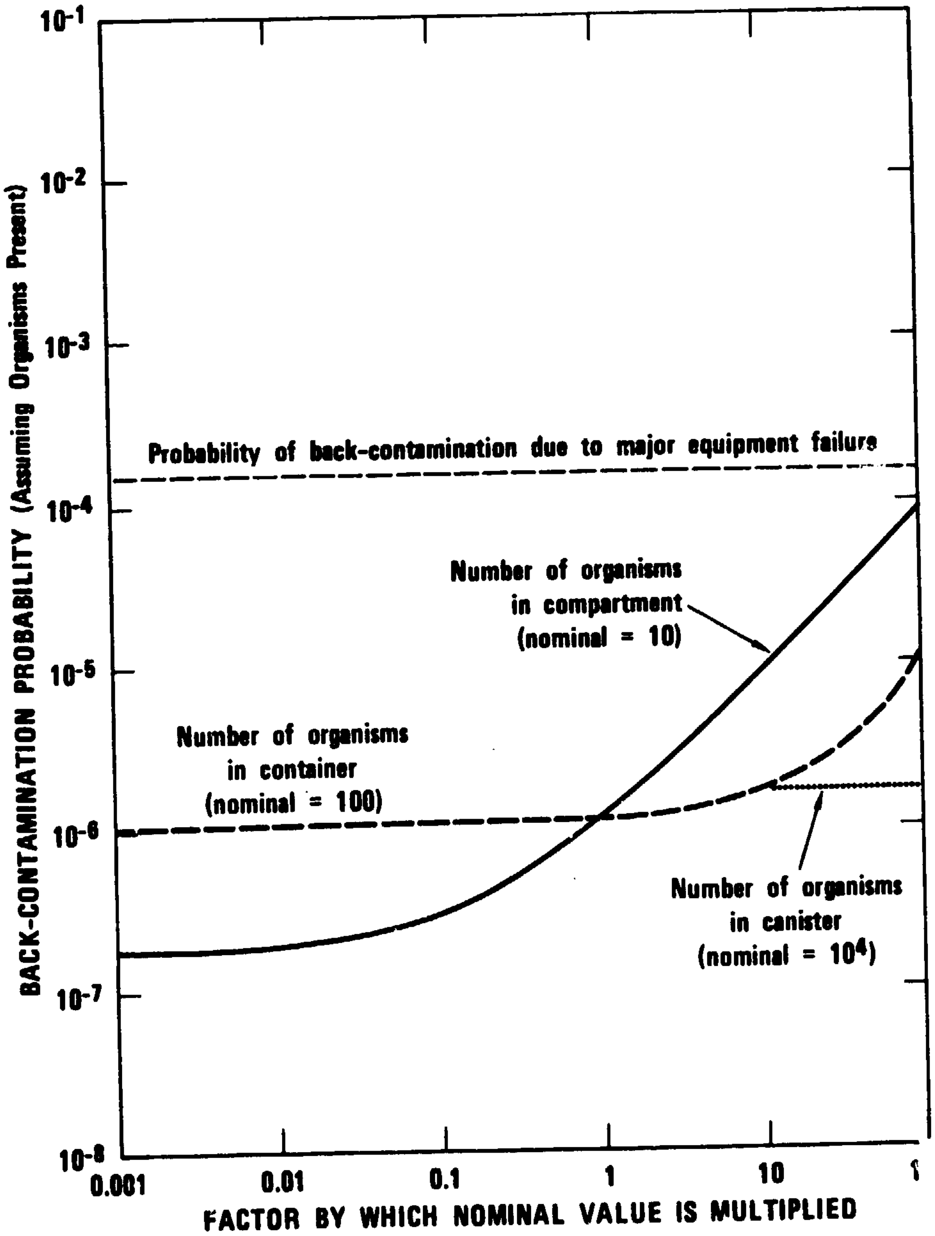

FIGURE 4.8 PROBABILITY OF BACK-CONTAMINATION DUE TO LEAKAGE SENSITIVITY TO NUMBERS OF MARTIAN ORGANISMS ASSUMED IN VARIOUS LOCATIONS

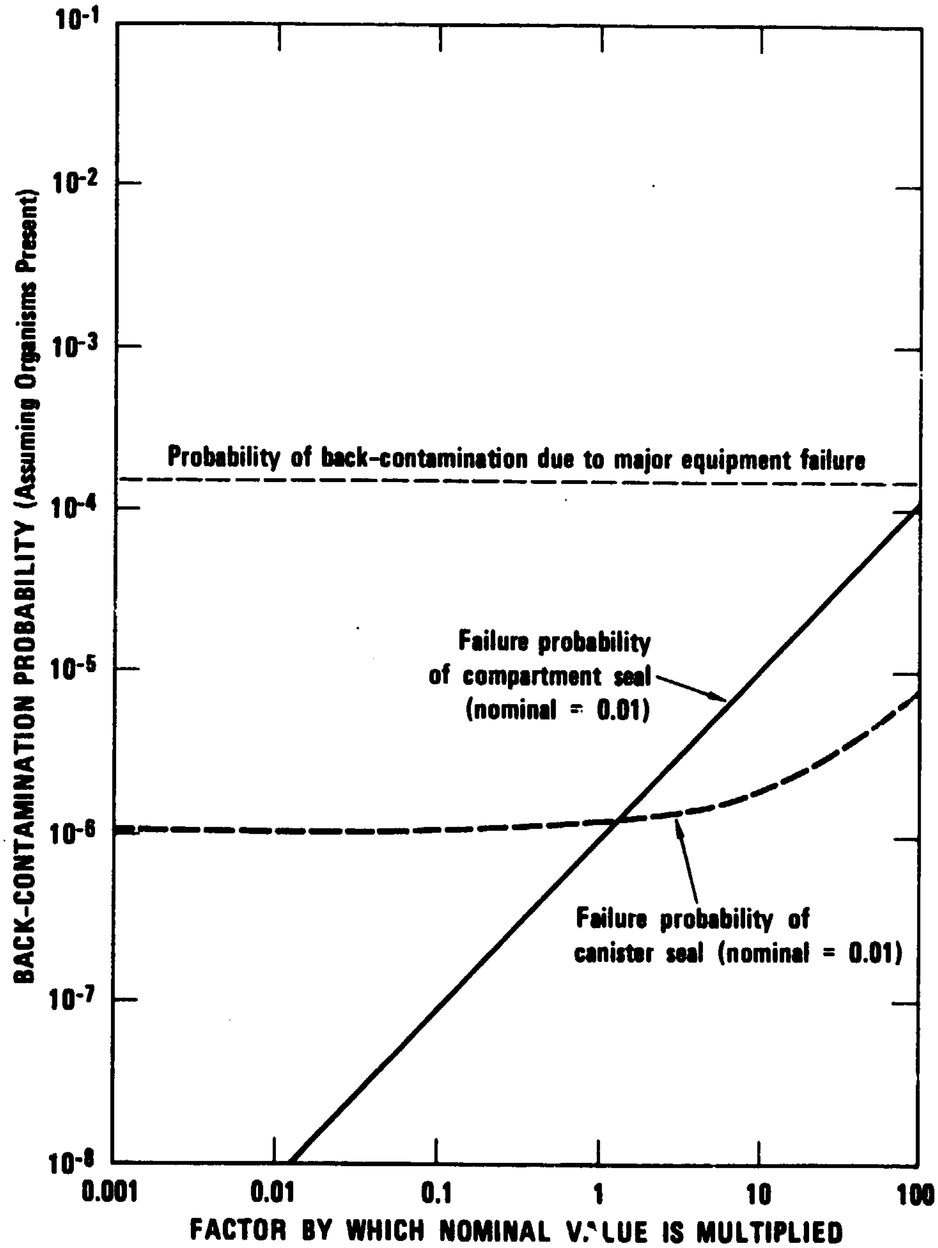

FIGURE 4.9 SENSITIVITIES TO SEAL RELIABILITIES

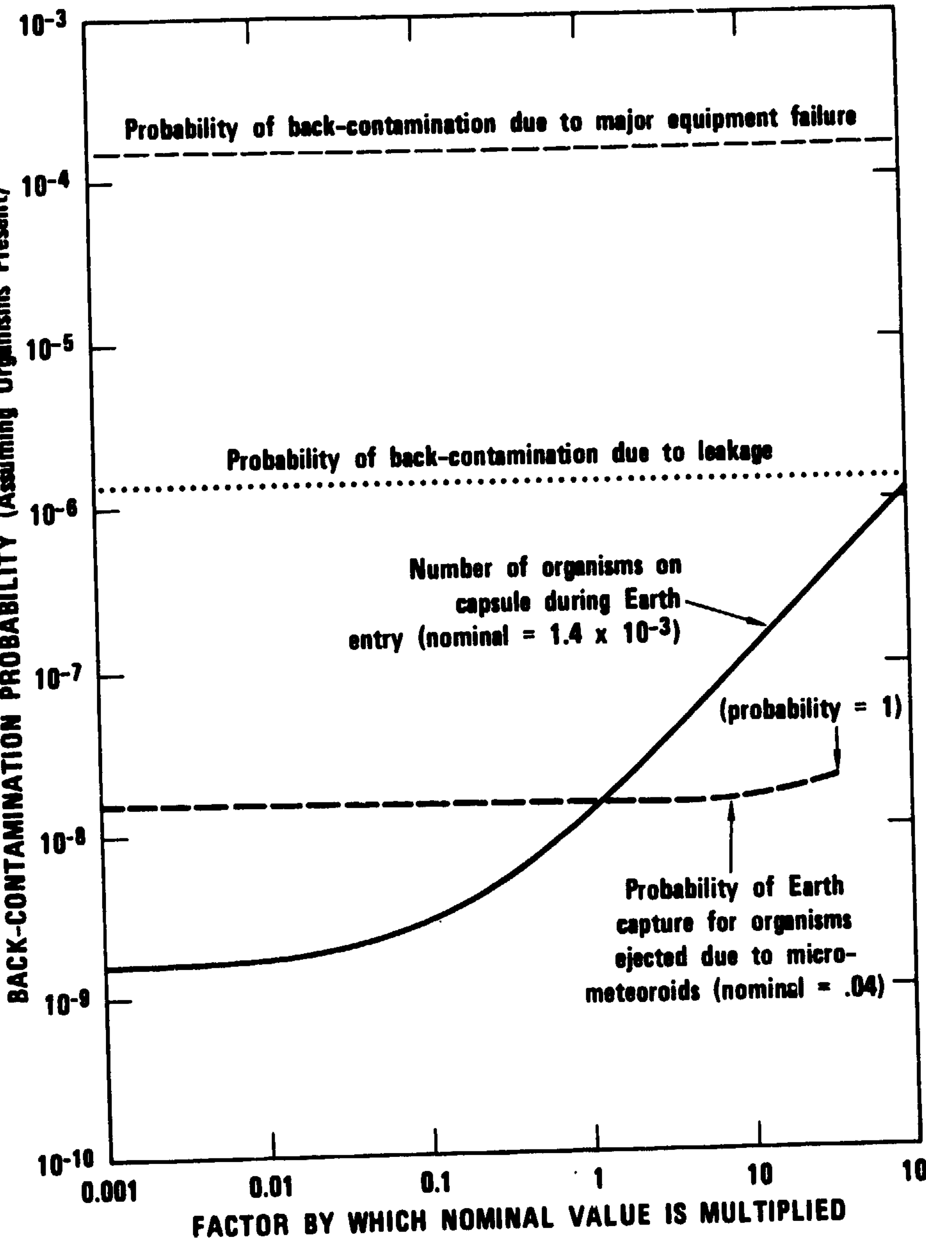

FIGURE 4.10 SENSITIVITIES TO THE NUMBER OF MARTIAN ORGANISMS ON THE EARTH ENTRY CAPSULE EXTERIOR AND THE PROBABILITY OF EARTH CAPTURE OF DISLODGED ORGANISMS

exothermic coating that is ignited just prior to the sealing of the sample compartment.* It is difficult to reduce the probability of back-contamination by more than about an order of magnitude because this would require simultaneous attention to several factors.

The most sensitive assumptions of all, of course, are the assumptions about the existence and viability of life on Mars. The analysis described in Chapter III not only assumes that life exists, it assumes that organisms will be transferred to the spacecraft and that the organisms in the samples will survive the return trip to Earth. A very conservative assumption is made concerning the survivability of Martian organisms on Earth. The assumption is that each released organism independently survives or dies with the same probability, depending on the manner of release. As described earlier, this has the effect of virtually guaranteeing that at least one Martian organism will survive if a large enough number are released.

To obtain the actual probability of back-contamination, the probability of contamination computed for the reference mission must be reduced by consideration of the probabilities that (1) life exists on Mars, (2) living organisms will be transferred to the spacecraft and survive the return trip to Earth, and (3) Martian organisms will be capable of surviving on Earth. Therefore, the computed probability of back-contamination is most sensitive to the conservative assumptions made concerning Martian biology. We must conclude that an analysis designed to assess the probabilities of possible characteristics of Martian organisms is essential for an improved estimate of the actual risk of back-contamination.

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*As mentioned in a report by Jaffe et al.,[5] the risk due to leakage could also be reduced by installing one or more transducers to detect pressure changes in either the sample compartment or sample container. Significant pressure changes would indicate seal failures that may be sufficient cause for a mission abort.

V MAKING DECISIONS ABOUT ALTERNATE MISSION PLANS--THE USE OF A CONTAMINATION PENALTY

In the previous chapters we described and illustrated a methodology for assessing the probability of potential back-contamination for MSSR missions. The real power of the methodology, however, is that it provides a framework for making decisions among various mission designs. One of the most basic mission decisions is the means of bringing the sample to Earth (e.g., direct Earth entry versus orbital recovery versus analysis in an orbiting laboratory). Other decisions are in the context of the overall mission plan chosen; assuming direct Earth entry, a decision must be made whether to have the capsule enter Earth over land or over the ocean, and whether or not to attempt an airborne snatch of the sample. In addition, decisions must be made about what, if any, systems should be installed for aborting the mission or sterilizing the sample in the event of deviations from the mission plan.

It is doubtful that decisions such as these can be made in a logical and consistent manner unless criteria for decision making are established. What criteria should be used? The simplest answer is, "Choose that mission design which gives the lowest probability of back-contamination." However, a little thought will convince us that this criterion is inadequate, for among the range of possible mission designs is always the alternative of flying no sample return mission at all. This alternative has a probability of back-contamination equal to zero, and so the simple criterion above would always lead to no mission being flown, regardless of the scientific value of the mission or the extent to which improved understanding and mission planning could be used to reduce the risk of contamination.

Actually, the probability of back-contamination is but one criterion for determining mission desirability. Others include:

- The value of the mission (both direct benefits, such as improved science and technology, as well as indirect social benefits, such as enhancing U.S. prestige).
- The probability of back-contaminating Earth with Martian organisms.
- The probability of contaminating Mars with Earth organisms.
- The economic cost of the mission.

5.1 A Framework for MSSR Mission Decision Making

To make intelligent choices among mission designs, responsible decision-making agencies must consider the information and uncertainty surrounding the decision and carefully weigh the relative importance of each of the attributes characterizing mission desirability. The principal difficulty here is that interested parties to whom the decision-making agencies are responsible often have widely differing states of information and uncertainty, differing preferences, and even differing models of the way events are related. For example, some scientists believe that the probability of life on Mars is insignificant. Others believe that this probability is quite high. Likewise, some scientists would argue that the scientific value of returning a Martian sample to Earth would be enormous, even if it were found to contain no life. Others might feel this value to be debatable. The role of quantitative analysis in social decision making is to facilitate the decision-making process. It accomplishes this by organizing the factors relevant to the decision so that specific areas of disagreement can be identified and the implications of the disagreement can be measured.

Quantitative analysis is more likely to fulfill this role successfully if a well-organized framework for decision making is established first. Figure 5.1 shows a decision framework for sample return mission planning. The framework graphically illustrates the relationships among the three fundamental considerations that have a bearing on the decision-making process: alternatives, information, and preferences.

The alternatives include mission design and containment policies (including, of course, whether or not to conduct the sample return mission at all). The outcomes to the mission are some level of scientific achievement and information, a possible effect on the Earth's ecosystem, a possible effect on Mars, and a mission economic cost. For the purposes of identification, key influential but uncontrollable factors are identified as "state variables": these include such things as whether life exists on Mars, the contents of the sample, the nature and timing of accidents, the adaptability of Martian organisms to Earth environment, and so on. Information enters the decision in two places: in a system model that describes what is known about the relation among decision, state, and outcome variables, and in describing our knowledge or lack of knowledge about the probable values of the state variables. Preferences are represented on the right-hand side of Figure 5.1 as a "value model." The value model includes an explicit expression of the decision-making body's willingness to make trade-offs between outcome measures.

Used properly, a well-organized quantitative model such as that schematically represented in Figure 5.1 can serve several important functions in social decision analysis. First, it can be used to identify those state variables and model elements that significantly influence the decision. We saw an example of this use in the sensitivity studies of the last chapter. Public review can then be focused on the issues that matter. Second, the model organizes the information in a concrete form

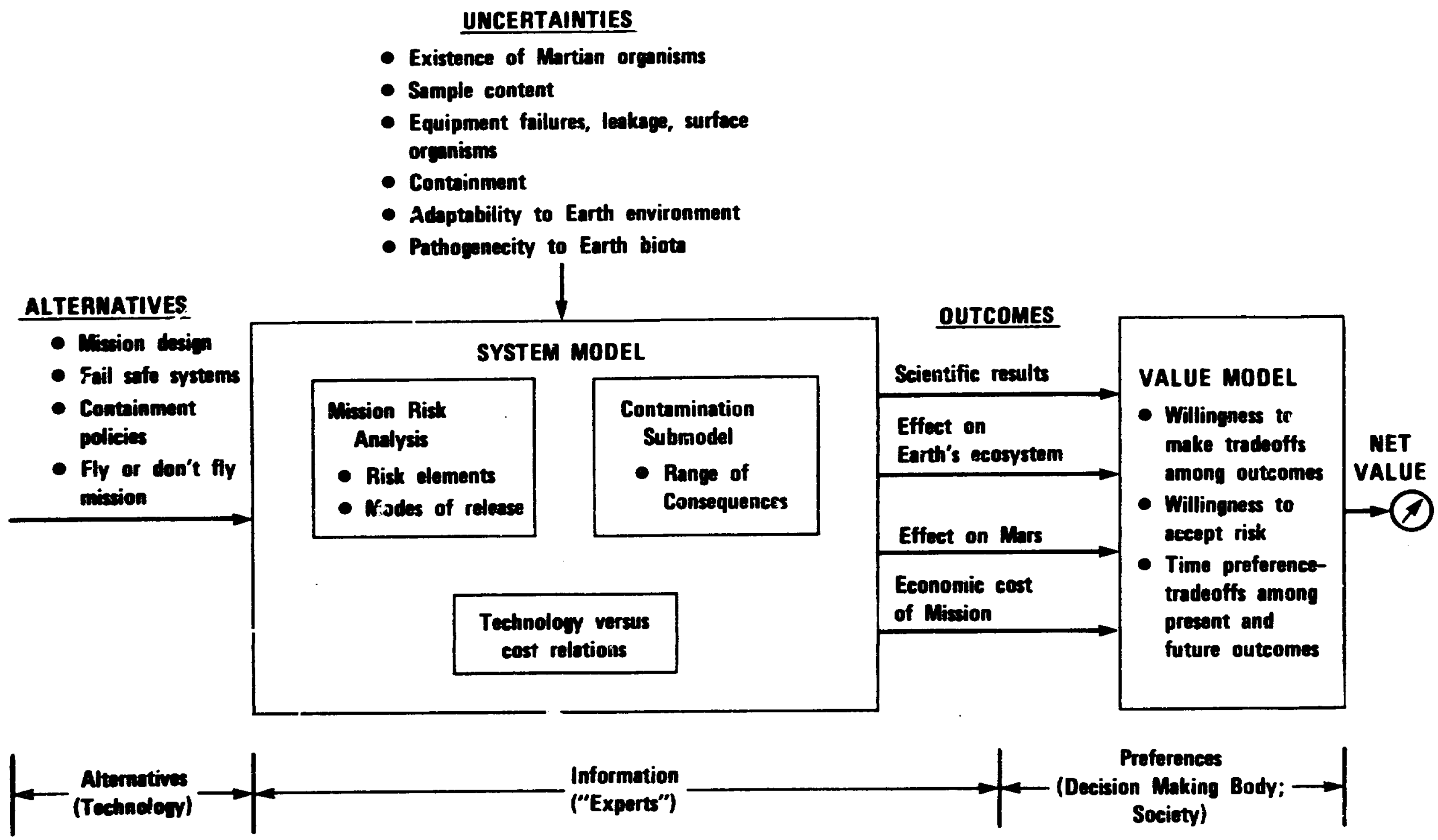


FIGURE 5.1 DECISION FRAMEWORK FOR MSSR PLANNING

so it can be constructively reviewed by all interested parties. Specific areas of disagreement can be identified, and the implications of the disagreement can be measured. Conflicts may often be avoided by demonstrating that the rational choice is the same despite disagreement over a particular value assessment or the estimate of the probability of some specific event. Explicit value trade-offs and uncertainty assessments, together with a system model such as that developed in the previous chapters, can focus the effort on those differences that do matter.

5.2 A Simple Example

To provide a simple example of how one would make decisions with the aid of the decision framework described above, we will consider an option for reducing the risk of back-contamination from the reference mission described and analyzed in Chapters III and IV. Recall that the major source of back-contamination risk was that of parachute failure during Earth entry. Therefore, we may wish to consider a system for incinerating the sample in the event of parachute failure. If the parachute system should fail to operate properly, such a system would automatically ignite a layer of exothermic material that would heat the capsule and its contents to several thousand ^{o}C in a few seconds, thereby providing a high probability of eliminating the possibility of contamination.

In determining whether we should really want such a system, we must also consider that incineration destroys the scientific value of the sample and that there might be some potential reliability problems with its use. For instance, the system may fail to operate when it is needed, or it may operate when it is not needed. One other possible problem may be that the rapid heating of the sample and capsule may drive off gasses that could conceivably cause the sample containment to rupture before sterilization is accomplished, spreading rather than killing the organisms.

To be specific, let us suppose that an incineration system is developed, and analysis of this system (experimental testing and the development of models to simulate its behavior if installed as part of the reference mission design) indicates that if the parachute fails, the incinerator will operate with a reliability of 99%. Its false signal rate, the probability that it will function when the parachute has not failed, is 1 in a 1,000. The probability that sample containment will rupture, causing the sample to scatter before sterilization is complete, is determined to be 1 chance in 100. These are purely hypothetical numbers, but they will be sufficient to illustrate the method. Figure

5.2 shows the modification of the tree structure for the probability of back-contamination from major equipment failure that is needed to account for the addition of the system fr . incinerating the sample. In this illustrative example, we see that the probability of potential contamination is reduced from 1.6×10^{-4} to 4×10^{-5}, a reduction of a factor of four.

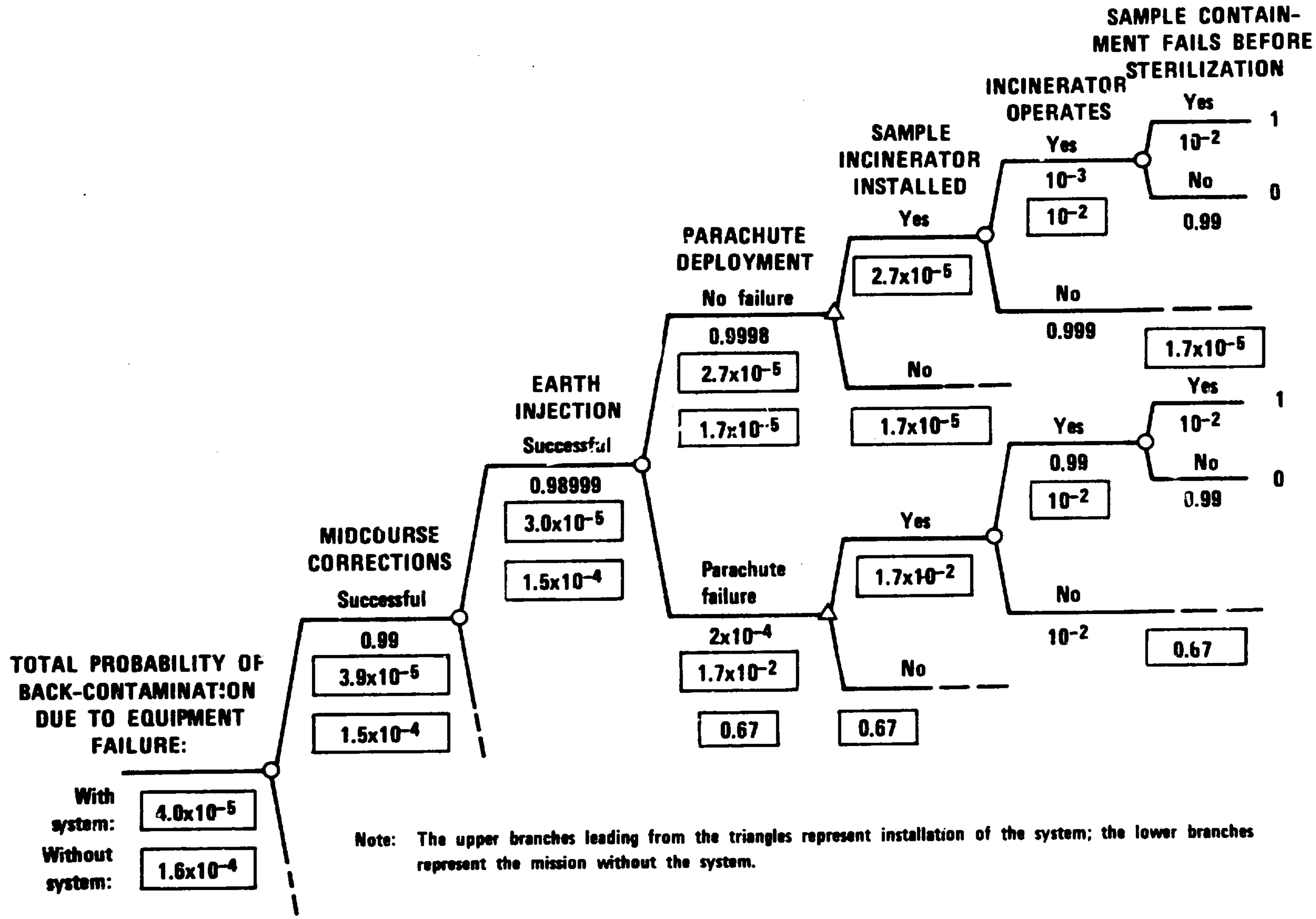
It is easy to understand the reasons for the magnitude of reduction obtained. In Chapter IV the sensitivity of the probability of potential contamination to the probability of parachute failure was computed (Figure 4.2). Even though parachute failure was the single most critical risk element for the reference mission, the sensitivity analysis showed that the contamination probability could be reduced only by about an order of magnitude by eliminating the probability of parachute failure. Since the incineration system reduces but does not eliminate the contribution of parachute failure to potential contamination (and, in fact, adds the risk of explosive containment rupture) the factor-of-four reduction obtained above is understandable. Unfortunately, a fail-safe system that eliminates or substantially reduces the risk associated with one risk element has a relatively small impact on the overall risk because that overall risk arises from a large number of factors.

This leads to what may be a difficult decision for mission designers. Suppose the incineration system cannot be installed without reducing the mission science payload in some way. For example, the system may render monitoring and control of sample environmental conditions (e.g., temperature) more difficult and add weight and complexity, thus using resources that might otherwise be devoted to scientific aims. The question is, "Should the incineration system be installed, given that it reduces the contamination probability by a factor of four but also reduces the scientific value of the mission by a certain (known) amount?" The decision to install the system requires a judgment of the relative value of reducing the contamination risk versus the cost of reducing the scientific payoff of the mission.

The decision framework of Figure 5.1 suggests that this question is best answered by separating the value issues from the engineering and technological ones. The value issue is:

- How much reduction in the scientific value of the mission (or increase in mission cost) should be accepted in order to reduce the probability of contamination by a given amount?

The answer to this question is conveniently expressed by specifying the appropriate value for a "contamination penalty." Suppose we define v_d to be the value of a mission with a particular design d. This value takes into account both the scientific benefits of the mission and its economic costs but does not include the cost of potential back-contamination.



Note: The upper branches leading from the triangles represent installation of the system; the lower branches represent the mission without the system.

FIGURE 5.2 EFFECT ON BACK-CONTAMINATION PROBABILITY OF SYSTEM FOR INCINERATING SAMPLE IN THE EVENT OF PARACHUTE FAILURE

Let P_d be the back-contamination probability for the mission. The choice of an optimal mission design may be expressed mathematically as the maximization of the expected net value of the mission, defined as

$$\begin{array}{l}\text{Expected net} \\ \text{value of mission} \\ \text{with design d}\end{array} = E(v_d) - P_d K \quad , \tag{5.1}$$

where $E(v_d)$ is the expected mission value and K is a contamination penalty.* The contamination penalty K is expressed in the same units as mission value and determines the weight we assign to the risk of back-contamination in assessing the net value of a mission. The higher the value we assign to K, the lower the net value of the mission and the more inclined we are to trade off mission scientific value and increased economic costs in order to obtain a lower probability of contamination.

To illustrate, let us return to our example decision of whether to install an incineration system in the reference mission. To simplify, we will assume that the additional economic cost of installing the incinerator is negligible. but that its installation will result in a definite reduction in scientific value by a fraction δ. We will define a contamination penalty for the decision in units of the expected scientific value of the nominal mission design. Let the expected scientific value of the reference mission without the incinerator system be

$$E(v) = 1 \quad .$$

Then the expected scientific value with the incinerator is

$$E(v') = 1 - \delta \quad .$$

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*An expanded discussion of this approach (in the context of integrating outbound planetary quarantine requirements into mission planning) is contained in a previous SRI report.[6] Hirschleifer[7] and Howard[8] have pointed out the need to address directly the trade-off between increments of probability of a catastrophic outcome and a decision maker's willingness to pay (or accept payment). More complex formulations are possible. For example, more sophisticated calculations may employ von Neumann-Morgenstern utility to include the effect of risk aversion. For a discussion of the issues of risk aversion see von Neumann and Morgenstern[9] and Luce and Raiffa.[10]

The probability of back-contamination without the incinerator is 1.6×10^{-4}. With the incinerator the probability of back-contamination is 4×10^{-5}.* Following Equation 5.1, the expected net value of the mission without the incineration system is

$$\text{Expected net value without incineration system} = 1 - (1.6 \times 10^{-4})K \quad ,$$

and the expected net value with the incineration system is

$$\text{Expected net value with incineration system} = 1 - \delta - (4 \times 10^{-5})K \quad .$$

If the mission is not flown, no scientific value will be produced and no risk of back-contamination will be taken. Thus the expected net value of the alternative of not flying the mission is zero.

The best alternative among the three choices (fly the mission without the system, fly the mission with the system, or don't fly the mission) is that with the highest expected net mission value.

Figure 5.3 shows the optimal choice for this example as a function of δ and K. Regardless of δ, if the contamination penalty is high enough, the alternative of not flying the mission is optimal -- the mission results simply aren't worth the risks of contamination. For a given contamination penalty (say $K = 10^3$), the incineration system should be installed as long as the cost to the scientific investigations is less than a certain amount ($\delta = 0.1$ if $K = 10^3$) -- otherwise, the mission should be flown without the system. As the contamination penalty increases, the break-even δ (the amount of scientific value we are willing to give up to reduce the back-contamination risk) increases also.

Figure 5.3 illustrates that a given contamination penalty implies a certain optimal decision among the choices. Conversely, were the decision to be made without the use of a contamination penalty, it would be consistent with only a certain range of contamination penalty values. For instance, if installation of the incineration system results in a 1%

*Actually, as discussed in Chapter II, these probabilities should be attenuated by the probability that life exists on Mars, the probability that such life would be returned by the spacecraft, and the probability that released Martian organisms would reproduce on Earth. We ignore this for simplicity.

loss in science value (δ = 1%), the decision to install the system and fly the mission is optimal only for contamination penalties between about 10^2 and 2×10^4.

There are many decisions in designing a mission in which a trade-off between scientific value and probability of back-contamination must be made. These include the number and types of samples to gather on Mars, the choice of recovery method at Earth (e.g., direct Earth entry, orbital recovery with Earth analysis, or analysis in orbit), and whether to include various backup and fail-safe systems. Each of these decisions may be formulated as a trade-off between science values, economic cost,

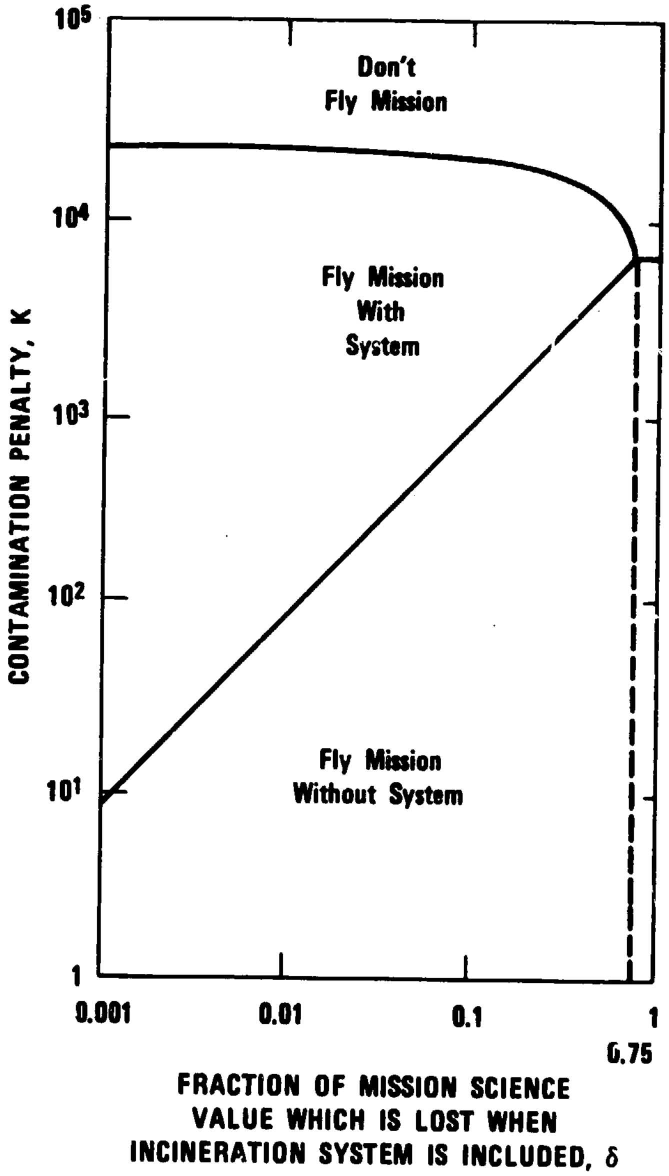

FIGURE 5.3 QUARANTINE VERSUS SCIENCE TRADEOFFS

and reduced risk of back-contamination. If each of these decisions is made without explicit reference to a contamination penalty, each may imply a different range of contamination penalties. If these ranges do not overlap, there will be no single contamination penalty for which the given decisions are optimal, and, therefore, the decisions will imply that inconsistent trade-offs are being made. On the other hand, if the contamination penalty is established at the outset, then the decision framework can be used to obtain decisions that consistently reflect the explicit trade-offs implied by that penalty.

Obviously, specifying the appropriate values for K and δ is a difficult task. However, it may not be necessary to specify the contamination penalty with great precision. The precise value of K will not affect the decisions to be made unless the specified point in the (K, δ) plane happens to be close to the boundary between two optimum alternatives. If it is close to the boundary, then the second best alternative is close in preference to the optimum, and a small error in K will not be of great importance.

This chapter has shown how a contamination penalty can be used in the context of a decision framework to clarify the decisions requiring trade-offs among different MSSR mission attributes. The following chapter discusses how one could go about determining a contamination penalty for an MSSR mission.

VI THE CONTAMINATION PENALTY

This chapter explores in more detail the concept of a contamination penalty and its application to sample return mission design decisions for which the risk of back-contamination is a consideration. We begin by defining more carefully the concept of a contamination penalty. Next we discuss the issues that should be considered in determining an appropriate value for the contamination penalty. Finally, we discuss the advantages and disadvantages of the use of a contamination penalty compared to other methods of providing guidance for decisions relating to back-contamination.

6.1 Definition of the Contamination Penalty

The definition of a contamination penalty may be inferred from the example of the last chapter. The contamination penalty, multiplied by the probability of contamination, gives the amount by which the value of a particular mission design should be penalized in the comparison with other mission designs to account for that particular mission's probability of back-contamination. Thus, the contamination penalty is the cost to be assigned per unit increase in the probability of contamination.

This may be clarified by a graphical illustration.* The simple mission design problem considered in Chapter V required a decision to be made between three mission alternatives: the reference mission without a system to incinerate the sample in the event of parachute failure, the reference mission with the incineration system, and the alternative of not flying the mission at all. To facilitate decision making, each strategy can be characterized by two numbers: a probability of back-contamination and the expected scientific value of the mission.† Figure 6.1 illustrates these three alternatives on a graph whose horizontal axis measures probability of contamination and whose vertical axis measures expected mission value. A δ (fraction of the mission value lost if the incinerator is installed) of 0.25 is assumed for the figure.

In general, many mission design alternatives will have varying levels of probability of back-contamination and expected mission value.

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*A similar graphical illustration is presented in a previous SRI report[6] dealing with outbound planetary contamination.

†Scientific value is defined here as the value of the benefits derived from the mission minus economic costs.

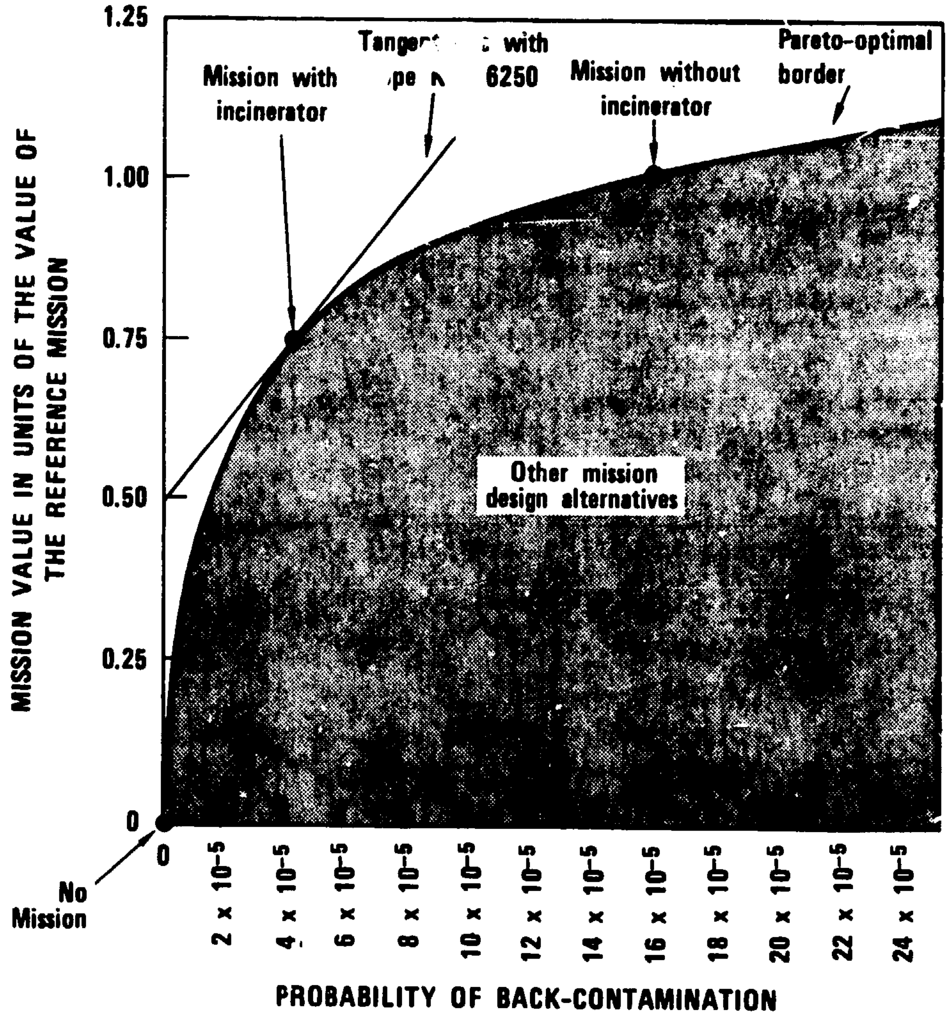

FIGURE 6.1 GRAPHICAL INTERPRETATION OF THE CONTAMINATION PENALTY

These other strategies are represented by points lying in the shaded region of Figure 6.1. Notice that no mission strategies exist in the region of the graph corresponding to both a very high mission value <u>and</u> a very low probability of back-contamination. If the mission is required to have a <u>very low</u> (relative to standard design) probability of back-contamination, it will require system redundancy to improve reliability, methods of verification, and fail-safe systems. This tends to decrease expected mission scientific value by increasing costs and weight and making monitoring and environmental control of the sample more difficult.

In choosing among the available strategies, we will obviously want to obtain a design with the lowest probability of contamination for a given expected scientific value. Similarly, for a given probability of contamination we will want a mission design that yields the highest possible scientific value. Thus, we will want a mission design that lies on the border of the region characterizing the set of possible strategies. This border, which is widely known in economic theory that deals with trade-offs among different objectives, is referred to as the Pareto-optimal border.*

A choice among strategies lying along the Pareto-optimal border requires that a trade-off be made between increments of expected value on the vertical scale and increments of probability on the horizontal scale. The ratio of these increments is the slope of the tangent line to the Pareto-optimal border. The slope of the tangent line that passes through the optimal mission design defines the contamination penalty.

Suppose the contamination penalty is K = 6250. The line with this slope is shown in Figure 6.1 to be tangent to the Pareto-optimal border at the mission design representing the reference mission with the incineration system. (The reader may verify from Chapter V that for a δ 0.25, K = 6250 is within the range of values for which this choice was shown to be superior to either the reference mission without the incineration system or that of not flying the mission.) If the contamination penalty is increased, the slope of the line increases and it will be tangent to a point with a lower probability of contamination and a lower expected scientific value. If the contamination penalty is decreased, the slope of the line decreases and tangency occurs for a point with a higher probability of contamination and a higher mission scientific value. Thus, the contamination penalty defines a trade-off between contamination probability and expected scientific value, and this trade-off implies a preference for a particular mission design.

6.2 The Contamination Penalty Versus the Cost of Contamination

Since the product P_dK of the probability of contamination P_d and the contamination penalty K is the reduction in expected mission value necessary to account for the risk of contamination, it is tempting to conclude that the contamination penalty is the reduction in value (cost) that should be assigned if the probability of contamination is one. If this is the case, then the contamination penalty should be the cost to society of back-contamination. This is not the case. Interpretation of the product P_dK as the reduction in mission value to account for the probability of contamination is only valid for small probabilities of contamination P_d. The contamination penalty is simply a number assigned for making trade-offs in a consistent way between small probabilities of contamination.

*Most modern textbooks on microeconomic theory discuss the concept of Pareto-optimality. For example, see Walsh.[11]

The situation is, in many respects, analogous to that of assigning a value to a human life in the context of decisions on automobile or aircraft safety. In this context, values of life such as $200,000 to $500,000 have been used.[12] It would be improper to assert that the value of life used in this context represents an amount an individual would pay to avoid certain death. Similarly, it would be improper to assert that the contamination penalty used in the context of a back-contamination analysis represents an amount society would pay to avoid certain contamination.

6.3 Determination of an Appropriate Value for the Contamination Penalty

Like the social "value of life," the contamination penalty should be representative of the values of society as a whole. The contamination penalty is society's way to tell mission designers of society's willingness to accept back-contamination risk in order to obtain the benefits of space exploration. As such, it should properly be set by a body responsible to the electorate. However, decision analysts, biologists, and other specialists should provide guidance in their areas of expertise.*

To assess a contamination penalty, it will be necessary to know the probability distribution over the range of possible consequences of contamination: Will actual back-contamination be a major ecological disaster comparable to the return of a great ice age, will it be a minor inconvenience, or might it even be beneficial?

Some conceivable effects of the contamination of the Earth with Martian organisms are:

- A Martian life form occupies a new ecological niche, and affects other life forms minimally, for example, by turning the Antarctic dry valleys red.
- It competes with or harms some forms of life relatively inessential to humanity, comparable to the loss of the great whales, or the replacement of one species of plankton by another.
- It hurts a plant or animal on which man depends, as does corn blight.
- It harms an activity, such as rendering cold storage ineffectual in preventing bacterial growth.
- It causes a new form of cancer.
- It causes a pandemic that kills the entire population of Earth.

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*For a discussion of the differing roles of experts and society as a whole in matters of this kind, see Barrager and North.[13]

Analysis should be initiated to model the range of conceivable effects of contamination and their relative likelihoods. Obviously, the present state of knowledge is such that there will be a tremendous amount of uncertainty in the assessment of the potential consequences of back-contamination. Nevertheless, available knowledge and information can and should be represented in the decision-making process. Methodology developed to model the consequences of disasters (including accidental release of radioactivity from nuclear power plants[14] and hurricanes[15] may be helpful to this effort.

At least two approaches can be used to determine a contamination penalty for sample return missions:

(1) Set a maximum probability of back-contamination for a nominal mission and use this to infer a contamination penalty.*

(2) Directly assess a contamination penalty through trade-off judgments.

The principal difficulty with the first approach is the determination of a rational method for establishing a maximum probability. One approach that has been advocated for establishing acceptable risk levels is to limit the probability of the event under consideration to some small fraction of the already existing probability of adverse effects of the same magnitude from other sources.†

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*For a discussion of how a contamination penalty may be inferred from a maximum allowable probability of contamination, see Howard, North, and Pezier.[6]

†Starr, Rudman, and Whipple[16] introduce the notion of a "risk uncertainty principle," risks due to risk modes not previously considered. For risks to Earth, they use the example of "a giant meteor destroys Earth." Using the observation that such events have not occurred in the existence of Earth, they find a minimum risk of 2.5×10^{-10} per year. They conclude: "...risks or system failure probabilities of less than 2.5×10^{-10} are not really worth considering as an unremovable risk threshold of 2.5×10^{-10} has been defined." Since this is a number with dimension $(\text{years})^{-1}$, one needs a characteristic time for the risk in order to define the risk threshold. Assuming a characteristic time for back-contamination risk of 20 years, we find that the risk threshold for planetary contamination is $20 \times (2.5 \times 10^{-10}) = 10^{-9}$ probability. One may want to set the maximum probability of plantetary contamination to be, say, 1% of this for conservatism and because this risk is introduced by man. This leads to a contamination penalty $K = 2 \times 10^{10}$ (in units of the expected scientific value of the nominal mission). Unfortunately, as discussed in the text, there are serious problems to using such an approach.

For comparison, one might wish to consider the probabilities of natural catastrophies, such as earthquakes and long-term weather changes, and potential man-made disasters, such as a massive nuclear exchange between the United States and Russia. Unfortunately, this approach fails to provide a logical method for taking into account the benefits that are expected from the decision that carries with it a risk. Intuitively, we should be more willing as a society to accept additional risk for larger potential gains.

The second approach, direct assessment of the contamination penalty, may be accomplished by breaking down the trade-off decision between risk and value into more fundamental trade-off decisions. Howard[8] proposes such an approach for the assessment of a value of life. Each of the possible consequences of contamination and their probabilities would be assessed; then individual trade-off decisions would be established to reflect the degree to which society is (or should be) willing to trade off those attributes it values (such as standard of living) in order to reduce the probabilities of the various consequences of contamination. The logic behind this approach is similar to the logic behind the analysis of the probability of rare events. It is easier to make each individual trade-off decision and infer the global trade-off than it would be to make the global trade-off between back-contamination risk and value directly.

Obviously, establishment of a contamination penalty will not be an easy task, regardless of the method chosen. However, it should be reemphasized that it may not be necessary to determine the appropriate contamination penalty to a high accuracy. If analysis of alternative MSSR mission designs in the decision-theoretic framework presented in Chapter V indicates that this is the case, very crude methods for estimating a contamination penalty may be adequate.

6.4 Alternatives to Using an Explicit Assessment of the Trade-off Between Mission Value and Probability of Back-Contamination

The alternative to using a contamination penalty as an explicit assessment of the trade-off between mission value and probability of back-contamination entails using such criteria as "best practical technology," or probability constraints that must be met irrespective of economics. The weakness of probability constraints is that they give no incentive to reduce a probability below the constraint threshold, and they may result in information that could show the constraint to be violated having a negative value. As a hypothetical example, on might "rather not know" whether a biological seal on a sample canister has leaked if in this case a constraint on back-contamination probability would be violated. Examples and further discussion of the weaknesses of a constraint formulation are found in Howard, North, and Pezier.[6]

Such qualifiers as "as low as practical," "safe enough," and "adequate safety" avoid the difficulty of assessing trade-offs, but they suffer from the same problems as do probability constraints, as well as ambiguity. Unless a balance is struck between the probability of release and the economics and science value of the mission, a negative incentive exists for the development of new technologies for reducing contamination risk and for obtaining more information about the effectiveness of the approaches for guaranteeing containment. In most cases only the costs of improvements will be reflected in the mission program. Any new technology that appears safer may be mandated; any new information showing a technology is less safe than previously supposed may result in rejection of that technology. Explicit trade-offs may be difficult to establish, but they provide a means for clarifying objectives and thereby ensuring that decisions are, in the broadest sense, cost-effective.

VII TOPICS FOR FURTHER RESEARCH

During the preparation of this report, consideration was given to additional research that would contribute to the development of a methodology needed to support decisions involving the risk of back-contamination from MSSR missions. The purpose of this chapter is to note briefly the further research work that has been identified.

7.1 Application and Extension of Assessment Methodology

a. An interesting and useful application of the methodology developed in this report would be an investigation of the alternative strategies that have been proposed for bringing a Mars sample to Earth. Three fundamentally different strategies that have been suggested are:

(1) Direct Earth entry (the reference mission for this study).

(2) Orbital recovery with analysis in an Earth-based sample receiving lab (Appendix E).

(3) Orbital recovery with preliminary analysis in orbit.

The methods described in Chapters II, III, and IV could be used directly to provide estimates of the risk of back-contamination from nominal mission designs based on each of these strategies. The results would indicate which risk elements associated with each mission strategy contribute most to contamination risk.

b. Given a specific strategy for sample return (e.g., direct Earth entry), an extension of the decision framework described in Chapter V could be used to determine a "best" mission design. The objective of this research would be to develop and illustrate a process for consistently making decisions regarding redundancy and the use of fail-safe systems to obtain a desired trade-off between back-contamination risk, mission cost, and expected mission scientific value. Since design decisions depend on the contamination penalty used, this research should show the impact on mission design of assuming different contamination penalties. An important result would be the insight this research would provide into the degree of precision necessary for establishing guidelines for MSSR mission planning (regardless of whether the guidelines are in the form of contamination penalties, probability constraints, or the like).

7.2 Development of Models for the Consequences of Releasing Martian Organisms on Earth

An obvious extension of current methodology is the development of models for estimating the consequences of releasing Martian organisms into Earth's biosphere. As explained in Chapter II, no attempt was made in this research to assess the probability of growth for Martian organisms released on Earth. Similarly, no attempt was made to quantify the range of possible consequences of back-contamination. An assessment of the probabilities of various consequences of contamination will be necessary before the probability of release computed for various sample return mission designs can be put in proper perspective.

While it is recognized that the limited extent of available information would constrain an analysis of the consequences of contamination, even a preliminary analysis, would be of value. For example, even a simple analysis would permit a computation of the value of resolving uncertainty. Identifying uncertainties with a high value of resolution may suggest specific experimental questions that could be answered by Viking, by experiments performed during possible future Mars missions conducted before a sample return mission, or by experiments performed during a sample return mission.

7.3 Methodology for Assessing and Operationalizing Contamination Penalties

Decisions about sample return imply a trade-off between the probability of contamination and the scientific value of the mission. Trade-offs made should reflect the values of society as a whole. However, as a practical matter, this decision may well be made in the legislative and executive branches of government in much the same way as decisions are made on other trade-off issues, such as emissions controls (trading off permissible pollution levels versus economic issues), nuclear safety (trading off the probability of accidental radiation release against the cost and supply of electricity), and recombinant DNA research.

The concept of a contamination penalty provides a logical means for consistently making trade-off decisions. Some of the issues surrounding the assessment and use of contamination penalties have been discussed in this report and elsewhere.[8] Much additional research needs to be done. Principal areas of research include determining the accuracy with which a contamination penalty must be specified and determining methods for obtaining assessments of contamination penalties to the required degree of accuracy. Clearly, the operational aspects of using a contamination penalty should be investigated. Specifically, a procedure should be designed for proceeding from a contamination penalty, such as that specified by a policymaking body, to the level of numerical specifications for individual components and processes (and methods of validation) that would be required for the efficient management of a large technological project, such as an MSSR mission.

Appendix A

SOURCES OF NUMBERS FOR INITIAL BIOLOAD

Appendix A

SOURCES OF NUMBERS FOR INITIAL BIOLOAD

Figure A.1 shows the numbers and locations of Martian organisms assumed in the analysis of the reference mission. A discussion of each of these assumptions is presented below. The discussions are not meant to be justifications for the assumptions. Indeed, the uncertainty in the numbers of Martian organism that would be present is such that no single number can be justified. The judgments are purely subjective estimates. The discussion is merely meant to indicate considerations that may be of relevance.

A.1 10^4 Martian Organisms (MO) in Sample Canisters

The basis of this assumption is an analogy with the biological content of Antarctic soil, which has been measured to contain between 1 to 2 organisms per gram on the north side of the "Last Mountain on Earth" (the southernmost mountain) and less than 100 organisms per gram in the sparsely inhabited dry valleys.[17] Assuming a density of between 1 and 100 MO/g implies 10^3 to 10^6 MO in a 1- to 10-kg sample. A middle value of 10^4 MO was chosen as the base case.

A.2 100 MO Inside the Sample Container

The container will be sealed on Mars' surface. The interior surface of the container and the outside of the canisters will have an area of about 1 m^2.

Data exist regarding the surface density of Earth organisms on the Viking lander bioshield, the Viking orbiters, and the launch-vehicle shroud. These were assembled in a clean room. The canisters will be loaded on Mars under more difficult conditions but without the presence of people to cause bioloads. As a very crude analogy we consider Viking numbers that indicate fo. Viking between 10^2 to 10^4 aerobic bacteria and between 10 to 10^3 spores per m^2 surface densities on the lander bioshield, orbiter, and launch-vehicle shroud. A nominal assumption of 10^2 MO per m^2 for the MSSR mission lander yields the assumption of 100 organisms.

A.3 10 MO Inside the Compartment

The container is passed to the Earth-return vehicle (ERV) in Mars orbit and sealed inside the compartment at that time. The exterior surface area of the container is about 0.5 m^2. An assumption of 10^2 MO per m^2

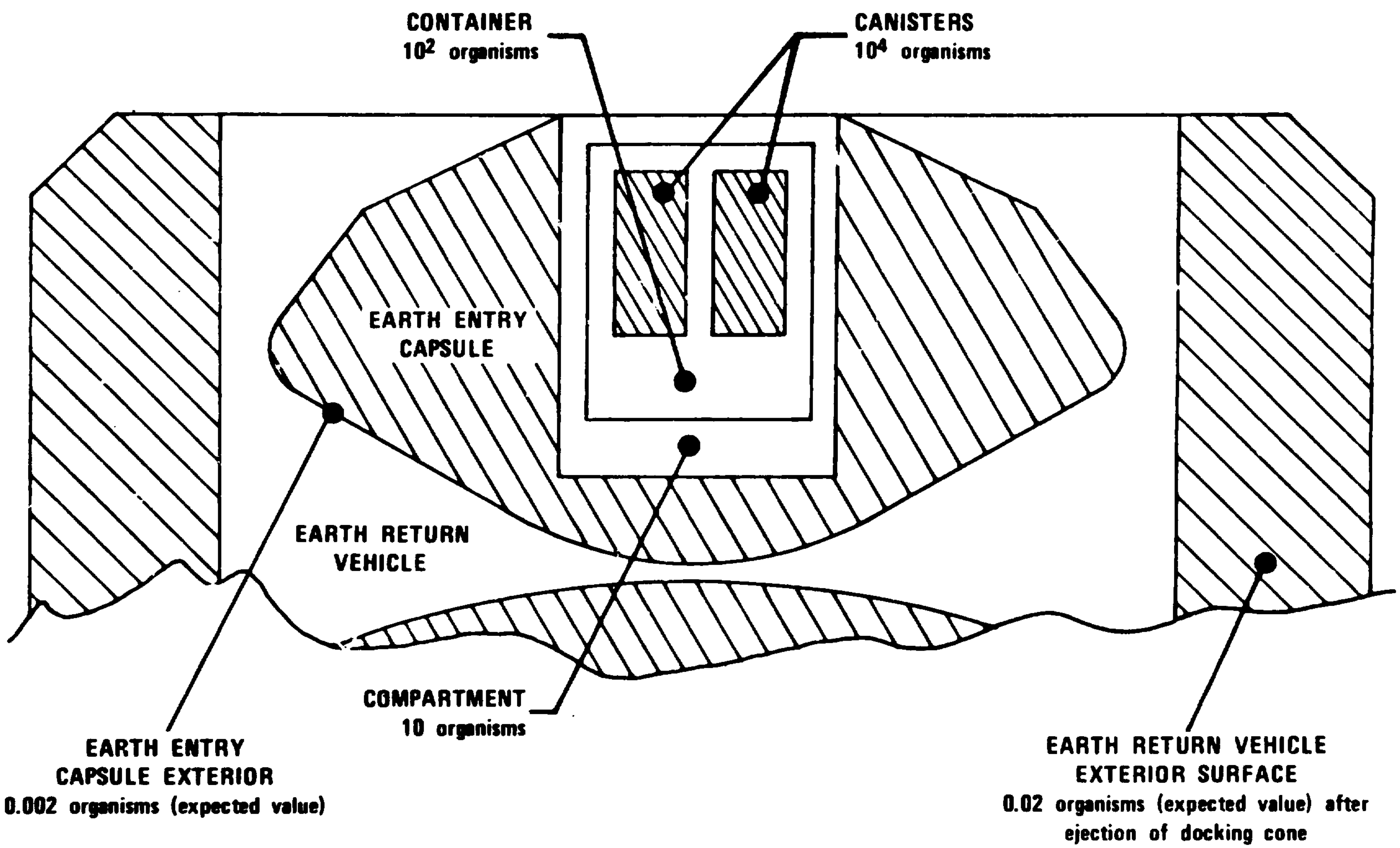

FIGURE A.1 ASSUMED ORGANISMS ON RETURN VEHICLE would imply 50 MO in the sample compartment. However, a smaller number, 10 organisms, is assumed because the bioload of the compartment could be reduced in a number of ways:

- When the compartment is sealed (brazed shut), its inside surface and the outside surface of the container could be heated briefly to partially sterilize it. One would have to take care not to heat the samples.
- A bioshield could be placed around the container on Earth, left in place on Mars' surface, and removed just before transfer of the container to the ERV. The area around the container seal could be sterilized with heat.

Reduction by an even larger factor should be possible. It is worth attempting, since, as shown in Chapter III and Appendix C, these organisms are the most likely source of contamination via leakage.

A.4 Expected 0.02 MO on the Outside of the ERV*

The ERV does not travel to Mars' surface. The only way MO can get on the surface of the ERV is from leakage of the sample or from transfer of surface organisms from the Mars-ascent vehicle (MAV) during rendezvous and sample transfer. We evaluate here the expected number of MO transferred from the MAV.

The MAV will be launched from the surface of Mars and be placed in Mars orbit, oriented with respect to the sun as shown in Figure A.2. The Mars-orbit vehicle (MOV), containing the ERV, will then maneuver and effect linkup. After the sample is transferred to the ERV, the MAV will separate from the MOV, taking the docking cone with it.

MO may be transferred to the ERV either generally during the period of station-keeping, when the MAV and MOV are in proximity, or specifically due to the acceleration of the linkup itself. The reasoning behind the assumed number of MO transferred is shown below.

(1) Transfer due to acceleration during linkup:

(a) MO on MAV exterior: 10^4 organisms (10^6 soil particles). Area: about 20 m^2 (500 MO per m^2--higher density because of greater duration of exposure).

(b) Worse-case acceleration during docking: 100 g. Larger accelerations are assumed to lead to mission abort due to damage. (Note: the nominal acceleration would be much lower, perhaps a few g.) Fraction of MO shaken off MAV during docking: 10^{-3}.

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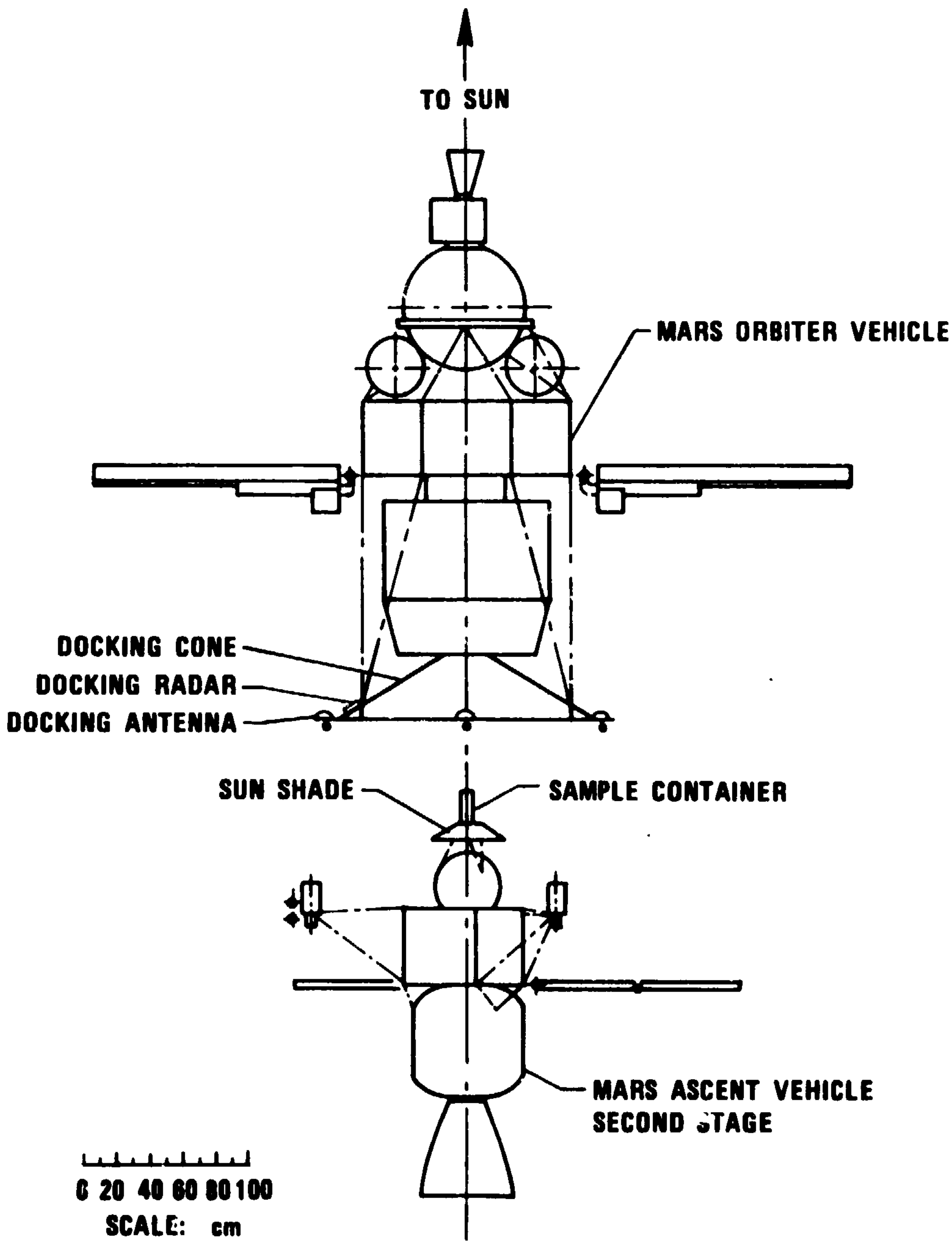
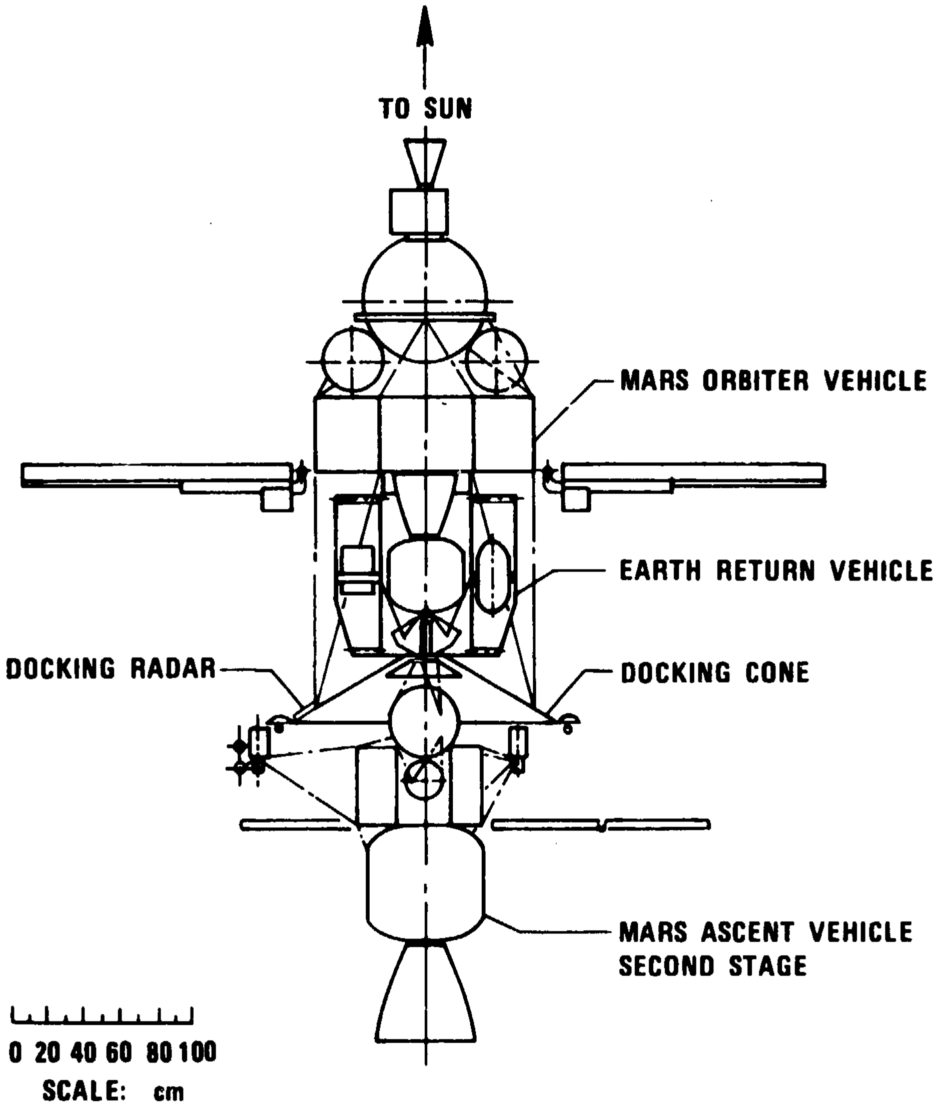
*Dr. Jack B. Barengoltz of JPL was very helpful in providing the estimates for this assessment.



(a) POSITION PRIOR TO DOCKING.

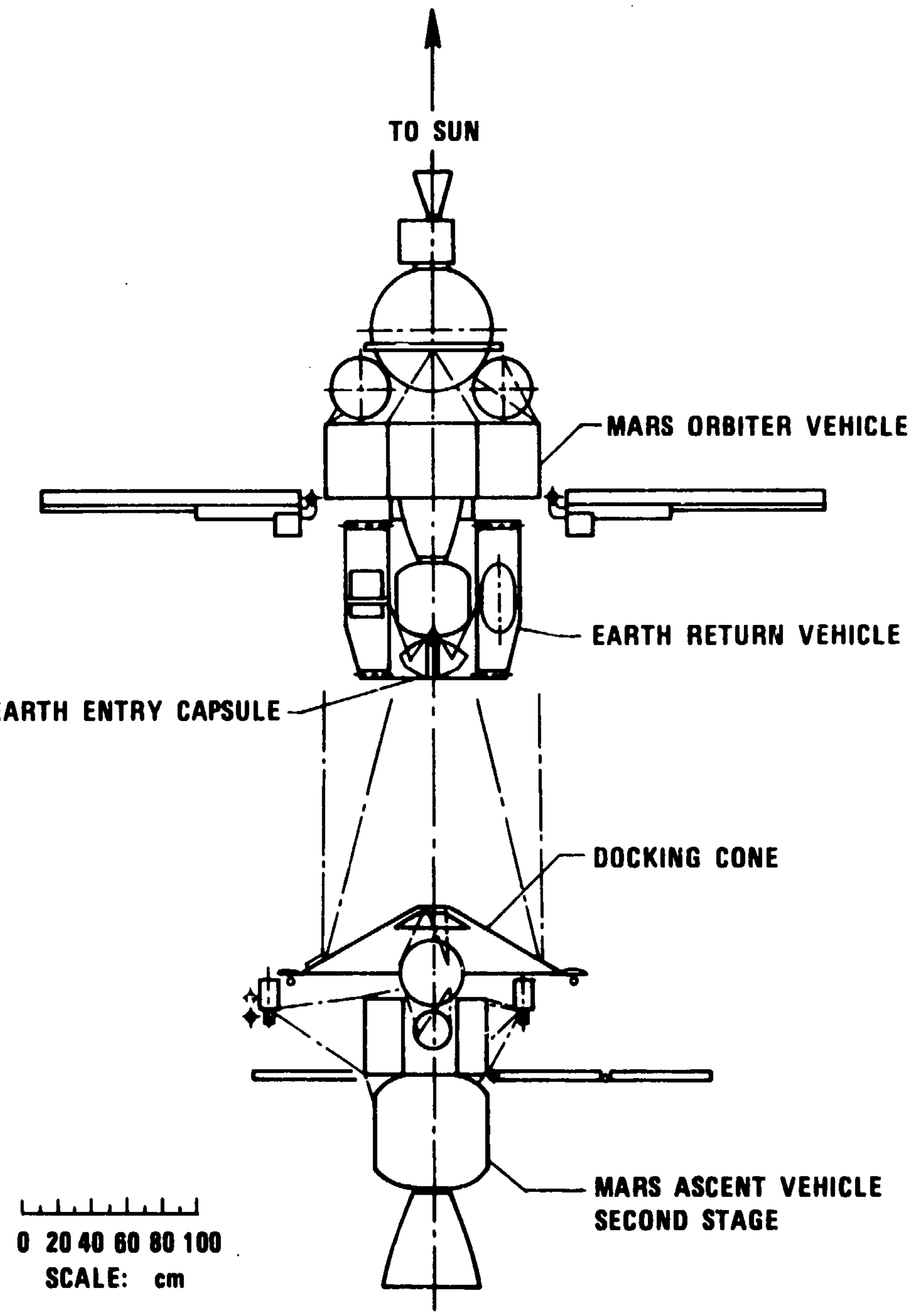
*Reproduced from reference 18.

FIGURE A.2 DOCKING SEQUENCE*



(b) DOCKED POSITION.

FIGURE A.2 DOCKING SEQUENCE (Continued)



(c) AFTER UNDOCKING.

FIGURE A.2 DOCKING SEQUENCE (Concluded)

(c) Fraction of organisms shaken off that land on the ERV: 10^{-3}. This number is strongly dependent on the geometry of the spacecraft. Most of the transfer is by direct line of sight. The docking cone (see Figure A.2) will shield most of the ERV from line of sight with the MAV. Most particles will be shaken off the MAV near the docking cone, since this area experiences the largest accelerations during docking.

(d) Expected number of organisms transferred during the docking acceleration: $10^4 \times 10^{-3} \times 10^{-3} = 0.01$.

(2) Transfer during station-keeping:

In addition to transfer of particles during the actual docking, transfer may occur during the station-keeping phase. There will be no line of sight then, and this transfer will depend on the interplay of solar radiation pressure and electrostatic forces. Anything shaded and ungrounded (as parts of the ERV will be) will tend to accumulate a negative change because solar wind electrons go in all directions while heavier protons in the solar wind travel in a straight line away from the sun. Shaded areas may have a potential up to three times the electron temperature, or -60 V. Areas in the sun will tend to get a positive potential due to the photoelectric effect. Particles coming off of the MAV solar panels may have a charge of +1/2 to +1 V.

For Viking, an expected 33 particles was computed to be transferred from the nonsterilized parts to the sterile landers during the one-year journey to Mars. The MAV and MOV will keep station for 3 or 4 days, or 1 percent of one year. However, there may be an enhancement over the Viking results by roughly a factor of 10 due to the larger turning radius of the particle trajectories allowed for transfer. On the other hand, there may be a factor of 3 reduction compared to Viking due to particle dispersal by the solar wind. (The MOV will be between the MAV and the sun, and particles will be emitted perpendicular to the MAV surfaces.) Thus, the expected number of particles transferred during station-keeping is roughly estimated to be

$$\underset{\text{(Viking)}}{33} \times \underset{\text{(Time Ratio)}}{\frac{1}{100}} \times \underset{\text{(Turning Radius)}}{10} \times \underset{\text{(Solar Wind)}}{\frac{1}{3}} \approx 1 \text{ soil particle.}$$

Assuming the conjectured 10^{-2} MO per Martian soil particle, this implies a transfer of 0.01 MO.

The fraction of MO transferred from the MAV to the ERV is strongly dependent on the geometry assumed. Careful design of the docking cone, used perhaps in conjunction with a simple bioshield, could possibly reduce this fraction substantially. On the other hand, if the docking cone were not installed, this number could increase by a factor of 10 to 100. Under the assumptions of this report, biological contamination on the spacecraft exterior surface is unimportant compared to the other sources of potential contamination.

A.5 Assumed Paths Followed by MO on the ERV

A discussion of the fraction of MO dislodged due to micrometeoroid impact, the fraction dislodged due to ΔV corrections, and the fraction that remain on the Earth-entry capsule (EEC) is given in Section 3.7.2.

Appendix B

PROBABILITY TREE--MAJOR EQUIPMENT FAILURE

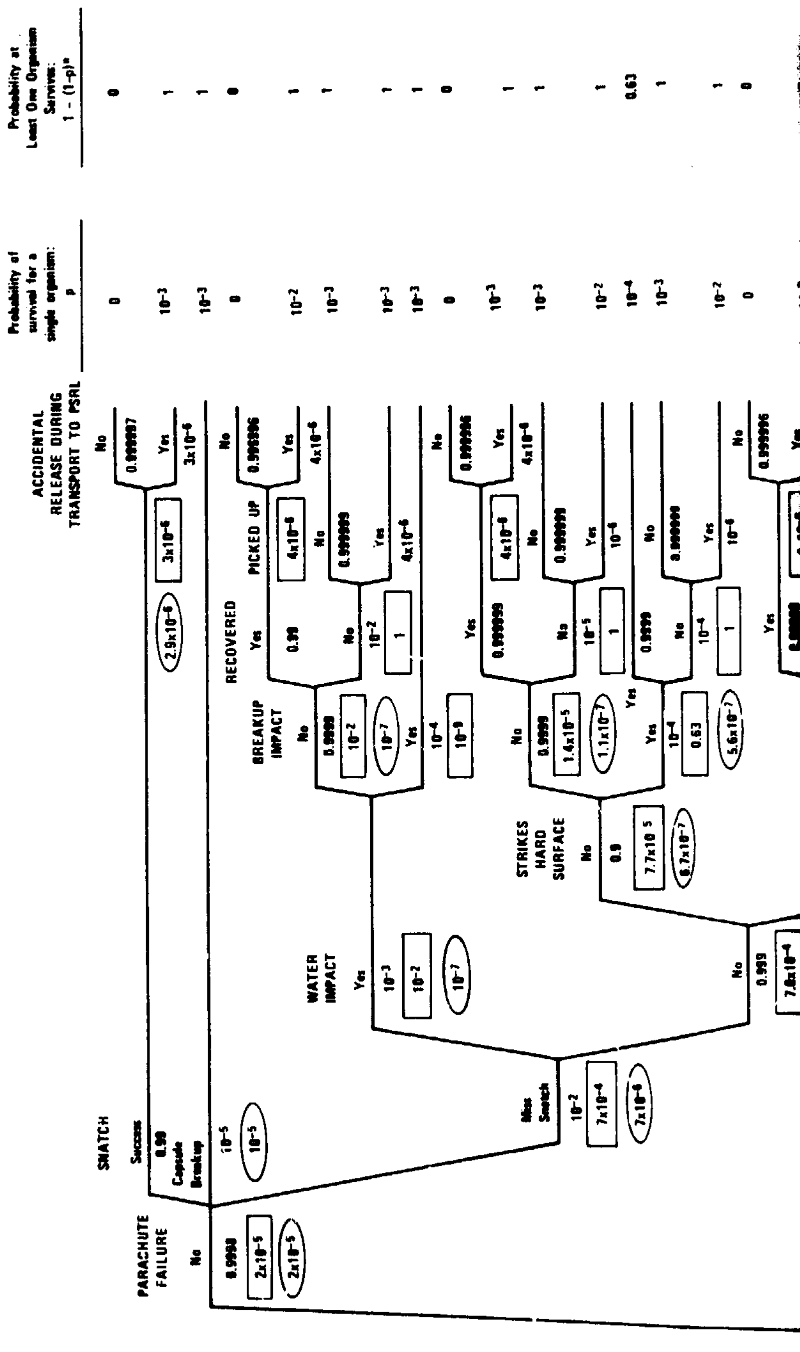
Appendix B

PROBABILITY TREE--MAJOR EQUIPMENT FAILURE

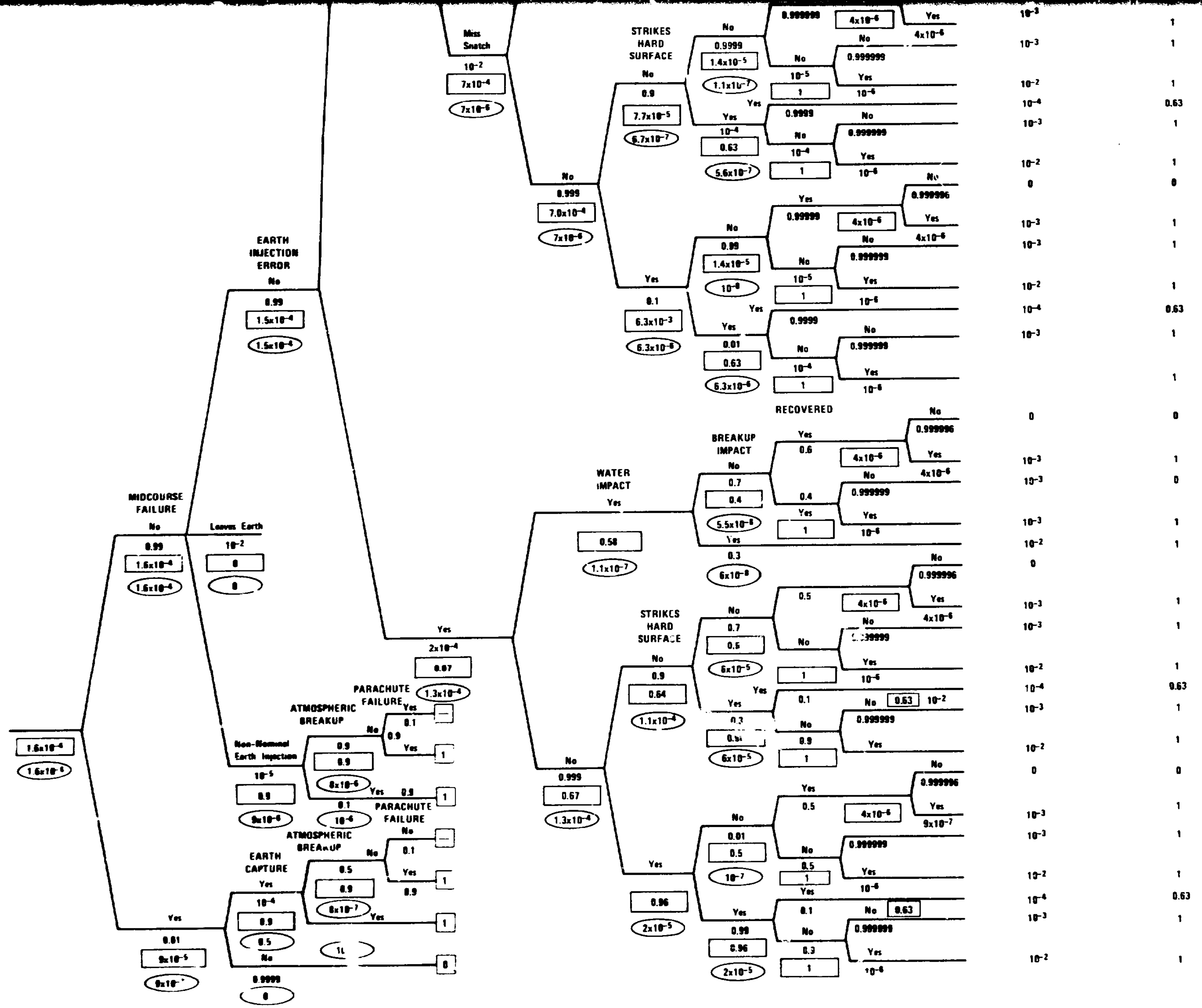
Figure B.1 displays the complete probability tree for computing the probability of potential back-contamination due to major equipment failure. The numbers under the branches of the tree not enclosed in boxes are the event probabilities assumed for the reference mission. Table B.1 defines the events and comments on the numerical values assumed for the event probabilities.

The numbers in square boxes in the figure are probabilities of potential back-contamination, conditioned on the events leading to that point in the tree. They are obtained by "rolling back" the tree -- multiplying the probability of each branch by the conditional probability of contamination on that branch and adding.

The numbers in ovals are the contributions to the contamination probability that come from all paths ("scenarios") leading through that point on the tree. They are obtained by multiplying the conditional probability of contamination at that point (square boxes) by the probability of reaching that point in the tree (the product of the event probabilities along the branches leading to that point). These numbers show the major factors contributing to the probability of back-contamination.



FOLDOUT FRAME 1



- Numbers under branches are conditional event probabilities
- Numbers in boxes are conditional probabilities of back-contamination
- Numbers in ovals are probability contributions of each risk element

FIGURE B.1 COMPLETE PROBABILITY TREE FOR MAJOR EQUIPMENT FAILURE

FOLDOUT FRAME 2

Table B.1

PROBABILITIES FOR MAJOR EQUIPMENT FAILURE EVENTS

Event Title	Definition	Assessed Probability	Comments
Midcourse failure	Loss of control of ERV trajectory during heliocentric transfer. Could be caused by either communications failure or failure of propulsion system.	0.01	Based on experience in designing similar systems at JPL. Probability of overall failure is assessed from probabilities of failure of individual subsystems and components, redundancy, and the number of corrective maneuvers required.
Earth capture	After midcourse failure, ERV impacts Earth's atmosphere.	10^{-4}	This is determined by the mission ΔV profile. The ΔV and aimpoint guidance policy and the resulting Earth impact probability are as assumed in Yen.[2]
Atmospheric breakup	Sample capsule breaks up in Earth's atmosphere.	0.5	Influenced by design of ERV, EEC, and sample container. The contamination probability is quite insensitive to this number; contamination is likely whether or not the capsule breaks up in the atmosphere.
Parachute failure (following midcourse failure)	Parachute system fails during non-nominal Earth entry--neither parachute slows the descent of the sample capsule.	0.9	If a midcourse failure occurred, some subsystems might not be working. The capsule is on a completely non-nominal trajectory, and has been out of control in space. There is little likelihood that parachutes will slow the descent.

Table B.1 (Continued)

Event Title	Definition	Assessed Probability	Comments
Earth injection error	The ERV is aimed to pass by Earth. The EEC separates from the ERV and is placed on an Earth impact trajectory by means of a solid-fuel rocket. Two things can go wrong:		
	• The rocket may fail to burn at all. In this case the EEC will likely continue past the Earth.	0.01	See discussion above under midcourse failure.
	• The rocket may burn incompletely, placing the EEC on a non-nominal Earth trajectory.	10^{-5}	Probability of entry outside 1^{o} entry corridor, based on Yen's[2] ΔV profile. It is unlikely that the solid-fuel rocket will fail to deliver the correct ΔV impulse, once it has been ignited. It is also unlikely that the EEC attitude would be non-nominal at the time of rocket ignition--if the EEC attitude has not been verified to be acceptable, the rocket will not be fired, leading to the previous case.
Atmospheric breakup, given non-nominal Earth injection	See above.	0.1	Questionable, but results are insensitive to this.
Parachute failure, given non-nominal Earth injection	See above.	0.9	See above

c-2

Table B.1 (Continued)

Event Title	Definition	Assessed Probability	Comments
Parachute failure (given nominal mission)	Failure of the parachute system to appreciably slow the capsule.	2×10^{-4}	Assumes two redundant parachutes. The chance of the primary parachute failing is taken to be 10^{-2}. Given that it failed, the backup parachute has a failure probability of 2×10^{-2}. The extra factor of two is to account for the possibility of common mode failures, or the same factor causing both parachutes' failure.
Snatch	The capsule and parachute will be snatched in mid-air by an airplane. (This method is used now in recovering military payloads--some data may be available from the Department of Defense.) During the snatch attempt:		Both of these numbers are quite uncertain.
	• The capsule can break apart, due to a collision with the airplane.	10^{-5}	
	• The snatch could be missed, the parachute and capsule would continue to Earth.	10^{-2}	
Water impact	The capsule lands in water (e.g., ocean, lake, river).	10^{-3}	This depends on the aimpoint of the trajectory--for example, the capsule could be aimed to strike water or land. The reference mission has been targeted to come in over land, because this leads to slightly lower overall probability of of contamination and a higher probability of recovering the sample (a lower probability of contamination results if a parachute opens, the snatch is missed, and and the capsule impacts on land).

Table B.1 (Continued)

Event Title	Definition	Assessed Probability	Comments
Strikes hard surface	Capsule impacts on hard surface--hard rock or equivalent. The categories "water," "hard surface," and "soft surface" are mutually exclusive and collectively exhaustive. Thus "soft surface" includes dirt, trees, houses, boats; everything not included in the other two categories.	0.1	Soft surface is more common than hard. This is an insensitive assessment.
Break up on impact	The capsule breaks up on impact with the surface, exposing a major portion of the sample to the ecosphere.	No parachute failure: 10^{-4} (water or soft surface) C.01 (hard surface). Parachute failure: 0.3 (water or soft surface) 0.99 (hard surface)	Break up is nearly certain if the parachute fails and the capsule strikes a hard surface.

Table B.1 (Concluded)

Event Title	Definition	Assessed Probability	Comments
Recovered	Capsule is recovered in the event of a missed snatch. Recovery with no breakup means no MO release. Recovery with breakup on land includes an effort to sterilize the area affected.	Depends on whether parachute failure or missed snatch occurs. See Figure B.1 for probabilities	The capsule is assumed to be equipped with a radio beacon, a flotation device, and a bright dye that is released on impact. Failure to recover the capsule can be caused by capsule entry in the midst of a severe storm.
Picked up	Discovery and dismantling of the capsule by an unauthorized person, who does not inform authorities.	10^{-6}	Given the publicity surrounding the mission and the effort to recover the capsule, it is most unlikely that it will be picked up after an unsuccessful search by the authorities. This is an insensitive assessment.
Accidental release during transport to planetary sample receiving laboratory	Any accident resulting in release before the sample is delivered to the PSRL.	If nominal mission: 3×10^{-6} If non-nominal mission: 4×10^{-6}	There are about 10^{-6} fatal accidents per operation (landing or takeoff) for the U.S. air carrier fleet.[18] Transport of the Martian sample should be at least as safe as this. This factor contributes negligibly to the overall probability of contamination. If it were more important, more elaborate precautions to assure transportation safety could be implemented.
Probability of survival	Probability of survival assumed for each MO released into the Earth's environment.	10^{-4} to 10^{-2}	Depends on method of release assumed and whether an attempt is made to sterilize location of release.

Appendix C

PROBABILITY TREE--LEAKAGE

Appendix C

PROBABILITY TREE--LEAKAGE

This appendix presents detailed assumptions and results for the probability of back-contamination due to leakage of Martian organisms (MO) from the sample compartment, sample container, or sample canisters on board the Earth-entry capsule. Figure A.1 illustrates capsule geometry and notes the numbers of Martian organisms assumed to be in each location. Note that leakage of organisms from the sample requires failure of all three seals. Leakage from the container requires failure of the container seal and compartment seal. Leakage of organisms from the sample compartment only requires failure of the sample compartment seal.

The analysis is conducted separately depending on the mission phase during which leakage occurs. The two mission phases considered are leakage during the last 30 days of heliocentric transfer (the contribution to contamination probability of MO leaked prior to this is considered negligible) and leakage during atmospheric entry.

Table C.1 defines events and provides comments on numerical values assumed in the construction of the probability trees. Figures C.1 and C.2 show the probability trees constructed from the events and probabilities in Table C.1.

The results of probability tree roll-back indicate that the probability of back-contamination due to the leakage component during heliocentric transfer (2.7×10^{-10}) is insignificant compared to that due to leakage during Earth entry (1.2×10^{-6}).

Table C.1

PROBABILITIES FOR LEAKAGE EVENTS

Event Title	Definition	Assessed Probability	Comments
Heliocentric compartment leakage	1% of the MO in the sample compartment is ejected during the last 30 days of spacecraft heliocentric transfer.	0.01	Probability based on estimated reliability of remote sealing. No pressure gradient would exist for this leakage mode, so estimated fraction of MO ejected may be overly conservative.
Heliocentric container leakage	Given compartment leakage, container seal also fails, releasing 10% of the exposed MO.	0.01	Since the container is sealed on Mars' surface, a pressure difference will contribute to particle release.
Heliocentric canister leakage	Given compartment and container leakage, one or more of the sample canisters leaks, ejecting 10% of the spacecraft bioload.	0.01	See above.
Survives heliocentric transfer	Ejected MO survive ultraviolet radiation and vacuum during orbital transfer to Earth's vicinity.	0.01	The assumption is that either all of the released MO will survive or that they will be intrinsically incapable of survival in space. A probability of 0.01 was chosen for consistency with Yen's analysis.[a]
Earth capture	Leaked MO eventually enter Earth atmosphere.	0.01	Probability based on analysis by Yen which assumes the ERV approaches the Earth from the side away from the sun.
Earth-entry compartment leakage	1% of the MO in the sample compartment is ejected during atmospheric entry of the capsule.	0.01	Pressure would oppose particle escape; however, a large hole might result in "breathing."
Earth-entry container leakage	Given compartment leakage, container seal also fails, releasing 1% of the exposed MO.	0.01	See above.
Earth-entry canister leakage	Given compartment leakage and container leakage, one or more of the sample canisters leaks, ejecting 1% of the sample bioload.	0.01	See above.
Probability of survival	Probability of survival for each MO released into the Earth's environment.	10^{-3}	Conjecture.

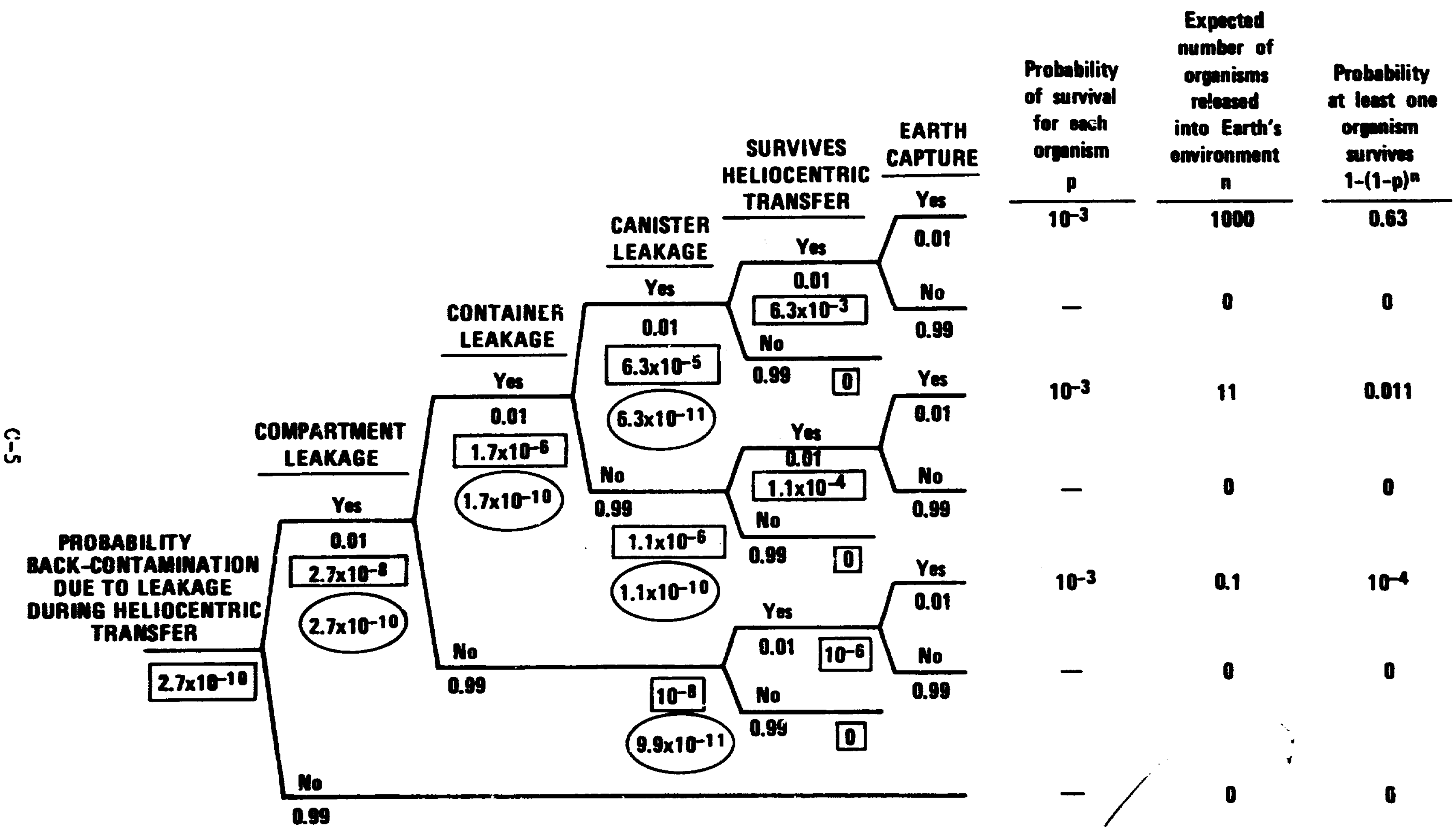


FIGURE C.1 PROBABILITY TREE FOR LEAKAGE DURING HELIOCENTRIC TRANSFER

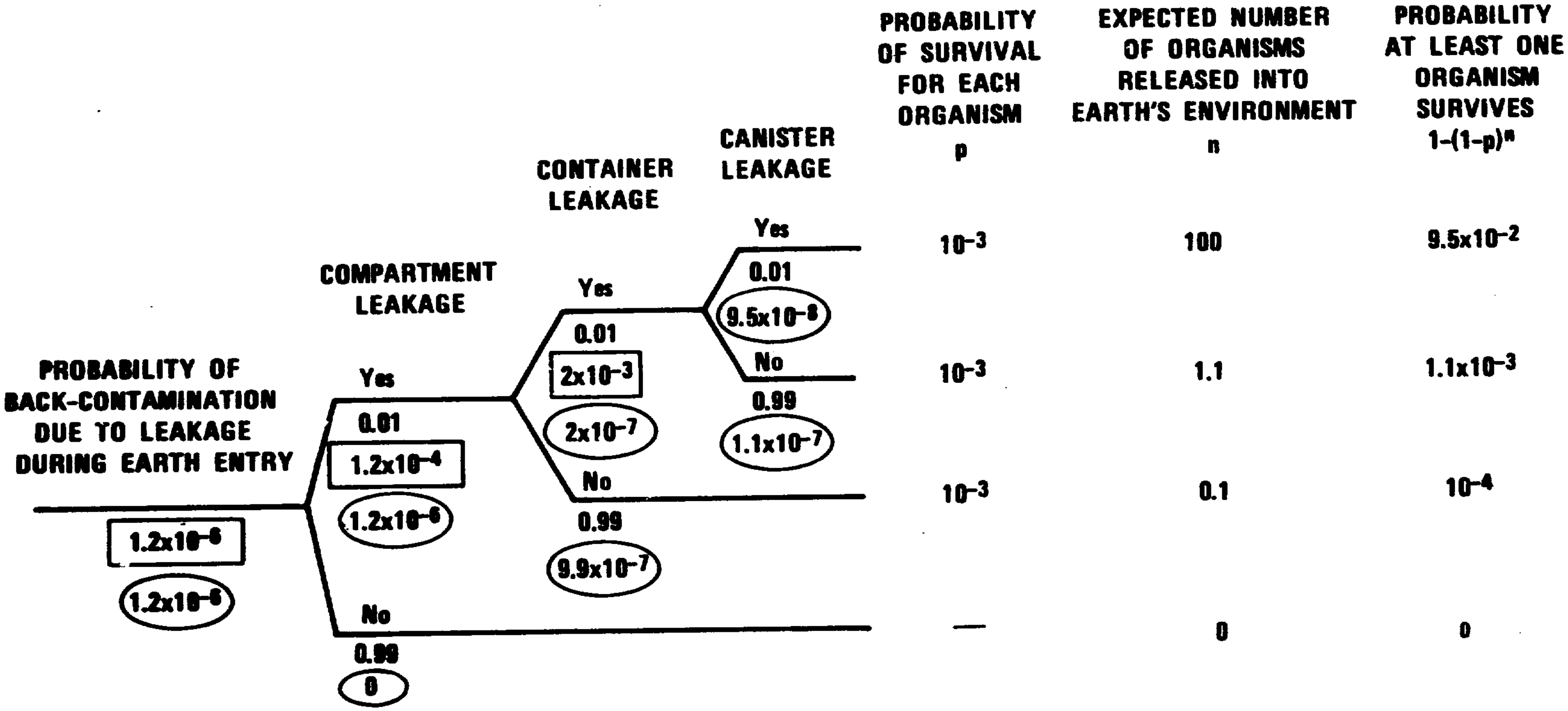


FIGURE C.2 PROBABILITY TREE FOR LEAKAGE DURING EARTH ENTRY

Appendix D

PROBABILITY TREE--SURFACE CONTAMINANTS

Appendix D

PROBABILITY TREE--SURFACE CONTAMINANTS

This appendix summarizes the analysis of the probability of back-contamination due to Martian organisms (MO) located on the exterior of the Earth-return vehicle (ERV). MO initially located on the ERV may be brought into the Earth's environment either on the surface of the Earth-entry capsule (EEC) or because they are dislodged prior to EEC recovery and follow a trajectory that results in Earth capture. Section 3.7.2 discusses the assumptions made concerning the expected fraction of surface MO that would follow various paths that may or may not lead to introduction into the Earth's ecosystem. Separate probability trees were constructed to analyze the risk from dislodged MO as opposed to that from MO that remain lodged to the EEC.

For a dislodged MO to result in contamination, it must survive heliocentric transfer, be captured by Earth, and survive once it enters Earth's atmosphere. For an organism that remains on the EEC to cause contamination, it must survive heliocentric transfer and capsule heat-up during entry. Simple probability trees representing these events for each of the five risk elements in the surface contaminants risk category are shown in Figure D.1. The results of the tree roll-back calculations are also shown. Table D.1 presents some comments on the probabilities assumed for the tree structures.

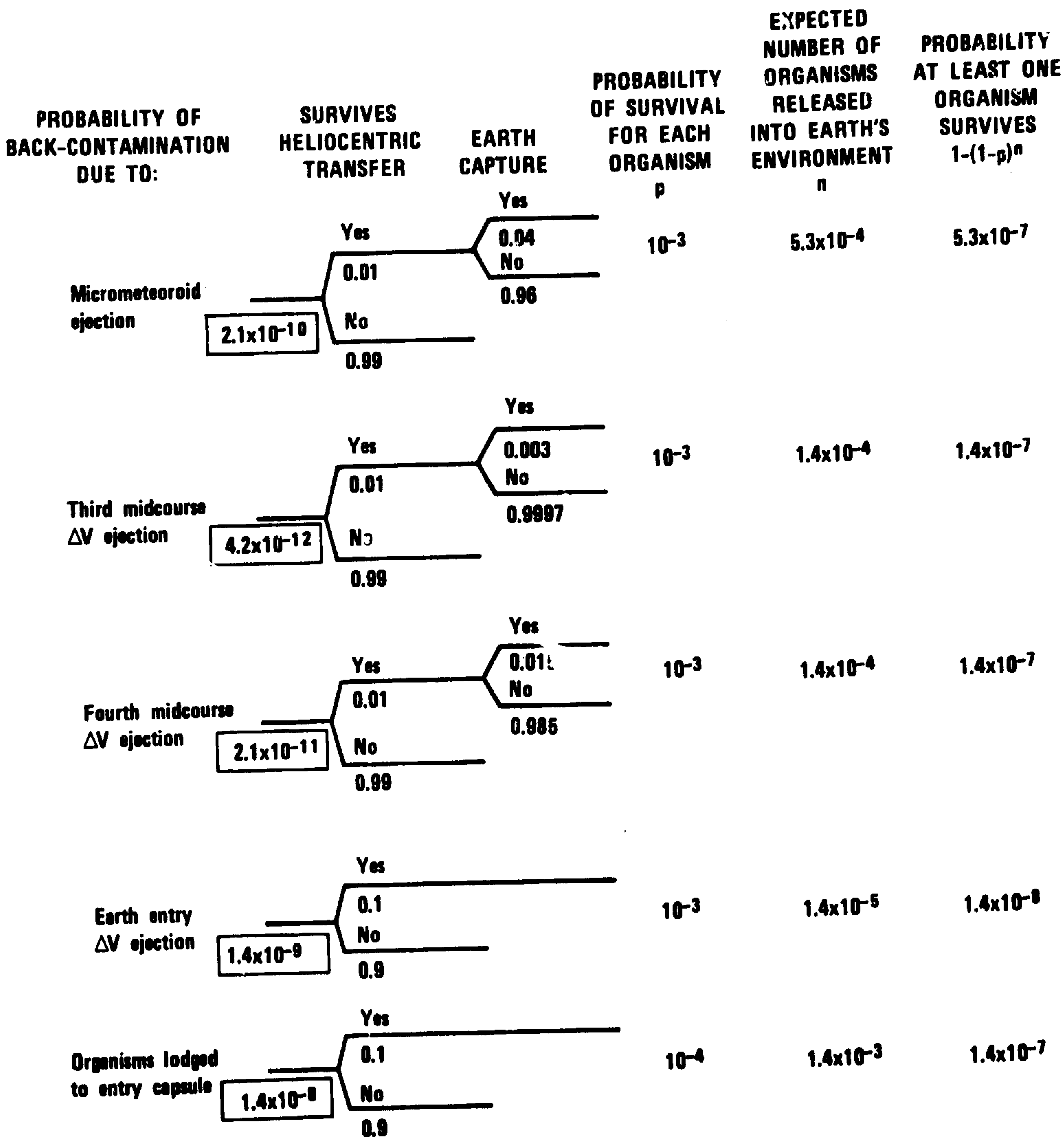


FIGURE D.1 PROBABILITY TREES FOR CONTAMINATION DUE TO SURFACE CONTAMINANTS

Table D.1

PROBABILITIES FOR SURFACE-CONTAMINANT-RELATED EVENTS

Event Title	Definition	Assessed Probability	Comments
Survives heliocentric transfer	**Dislodged MO survive ultraviolet radiation and vacuum during orbital transfer to Earth's vicinity.**	0.01 (dislodged particles) 0.1 (lodged on ERV)	For organisms dislodged during heliocentric transfer of the ERV, the assumption is the same as that used for MO ejected due to leakage. (See Table C.1, "Survives Heliocentric Transfer.") A higher survival probability is assumed for organisms that remain lodged on the ERV to account for the possibility of partial shading from ultraviolet radiation.
Earth capture	**Dislodged MO eventually enter Earth atmosphere.**	See Figure D.1	The capture probabilities depend on nature and timing of vibration that causes the MO to be dislodged. The probabilities assumed are those calculated by Yen.[2]
Probability of survival for each organism	**Probability of survival for each MO entering Earth's ecosystem.**	10^{-3} (dislodged particles) 10^{-4} (lodged on EEC)	Conjecture. The lower survival probability for MO lodged on the EEC assumes some sterilization due to reentry heating.

Appendix E

A PRELIMINARY ANALYSIS OF AN ORBITAL RECOVERY OPTION

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As noted in Chapter III, the largest source of back-contamination risk for the reference mission comes from events associated with the Earth-entry phase of the mission. A strategy of placing the sample in Earth orbit and recovering it by means of a space vehicle sent from Earth eliminates the principal Earth-entry-phase risk elements. The sample would not be opened or analyzed until it reached the planetary sample receiving laboratory (PSRL), located on Earth. This strategy thus differs essentially from that of analyzing the sample in an orbiting receiving laboratory based on the space shuttle. A brief preliminary analysis of the risk of back-contamination from an MSSR mission assuming orbital recovery is presented in this appendix.

Orbital recovery has the following advantages over direct Earth entry:

- With direct Earth entry, the date and rough location of the entry have to be specified about a year in advance, at the time the Earth return vehicle leaves Mars orbit. By putting the sample into Earth orbit, return to the Earth's surface can be scheduled to avoid bad weather or other short-term risks.
- With direct Earth entry, the Earth-entry capsule flies to Mars orbit and back, carrying all subsystems needed for Earth entry, such as heat shield, parachutes, flotation device, and padding in case of rough landing. By recovering the capsule in a space shuttle, one could obtain greater assurance of a safe Earth entry by enclosing the entire Earth-orbit capsule (EOC) in a big, strong, leakproof, sterilizable box. This box could also support maintenance of proper conditions for the sample during Earth entry (e.g., temperature).
- Shuttle recovery would ameliorate the problem of contamination from organisms located on the capsule surface. The capsule would be contained in a sealed box, which would only be opened at the PSRL. Any possible Martian organisms shaken off the EOC by the final orbital insertion maneuver would either settle back on the surface or disperse far from the EOC, assuming the EOC was allowed to stay in Earth orbit for some time before recovery.

We thus see that orbital recovery has potential advantages over direct Earth entry, in terms of both the problem of back-contamination and the preservation of the environment of the sample.

There are two options for recovery of the EOC from orbit:*

A. Direct recovery by the space shuttle. This would make use of the manned, routine, shuttle-entry mode. The EOC would be required to put itself into a near-Earth orbit accessible to the shuttle. This would require a large velocity change and consequently a large amount of propulsion carried to Mars orbit and back.†

B. Recovery from a 24-hour elliptical orbit. This recovery could be made by a vehicle constructed especially for the purpose, presumably an unmanned vehicle. The vehicle could launch from a shuttle in orbit or from the ground, capture the EOC, and transport it either to an orbiting shuttle or to the Earth. Alternatively, one would have to find a way to boost the shuttle into this difficult orbit. The EOC would be about the same mass as the Earth-entry capsule in the case of direct Earth entry--the extra propulsion required for orbit injection would balance off the weight saving due to removal of the unnecessary heat shield and parachute.‡

A preliminary analysis of Option A is presented below. The analysis serves as another example application of the methodology developed in this report.

E.1 Probability Tree Constructed for Analysis

Figure E.1 shows the probability tree for major equipment failure for orbital recovery option A. The event probabilities shown in the figure were assessed with the help of Dr. Harry N. Norton of JPL and are discussed briefly in Table E.1. The conditional probabilities of contamination are displayed in the figure in square boxes and the total contamination probabilities due to all possible scenarios containing a given node in the tree (risk contributions) are shown in the ovals. A major source of risk is the probability that accidental atmospheric entry will fail to sterilize the sample through heatup. Figure E.2 shows the sensitivity of the probability of back-contamination to this quantity.

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*We would like to thank Dr. Harry N. Norton of JPL for an informative discussion on this topic.

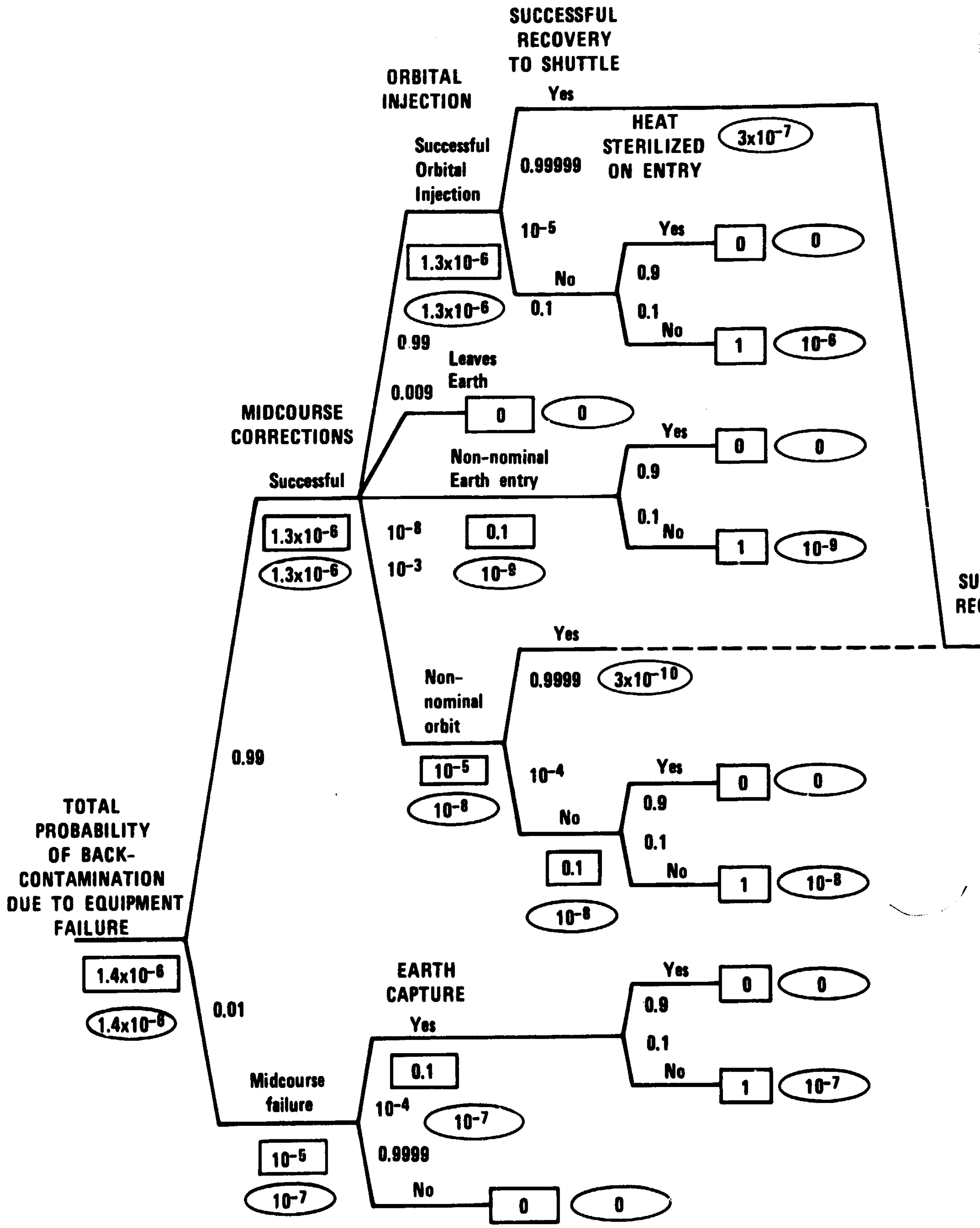
†See Figure 45 and page 118 in Weaver, Norton, and Darnell.[19]

‡Based on a comparison of Tables XXIII and XXIV in Reference 19.

Table E.1

PROBABILITIES OF MAJOR EQUIPMENT FAILURE EVENTS--ORBITAL RECOVERY

Event Title	Definition	Assessed Probability	Comments
Midcourse failure	See Table B.1.	0.01	See Table B.1.
Earth capture	See Table B.1.	10^{-4}	See Table B.1.
Heat sterilization on non-nominal entry	Heat generated by atmospheric entry is sufficient to sterilize the sample.	0.9	This requires a careful design of the ERV and EOC. The sample containment must hold together until the sample is sterilized. Sensitivity to this assumption is shown in Figure E-2.
Non-nominal orbital injection	There are several possibilities: • Leaves Earth--insufficient impulse to place capsule in orbit. • Non-nominal orbit. • Non-nominal Earth entry.	0.009 10^{-3} 10^{-8}	Similar to "Earth injection error" in Table B.1. Too little impulse will not put the capsule on a trajectory intercepting the atmosphere. It is difficult to imagine how this could occur.
Successful recovery by shuttle	Shuttle recovers EOC from orbit and places it in the strongbox.	0.99999 (EOC in nominal orbit) 0.9999 (non-nominal orbit)	If there are problems with the first attempt, another recovery attempt can be made. Recovery will not be possible if: • The EOC is lost in orbit and cannot be found. This would only happen if the radio pinger on the EOC fails, and it is not possible to locate it by passive means. • The EOC breaks apart in orbit, perhaps by collision with the shuttle or some space debris. In this case the Martian organisms would be exposed to a considerable period of solar UV before they drift down into the upper atmosphere.



FOLDOUT FRAME 1

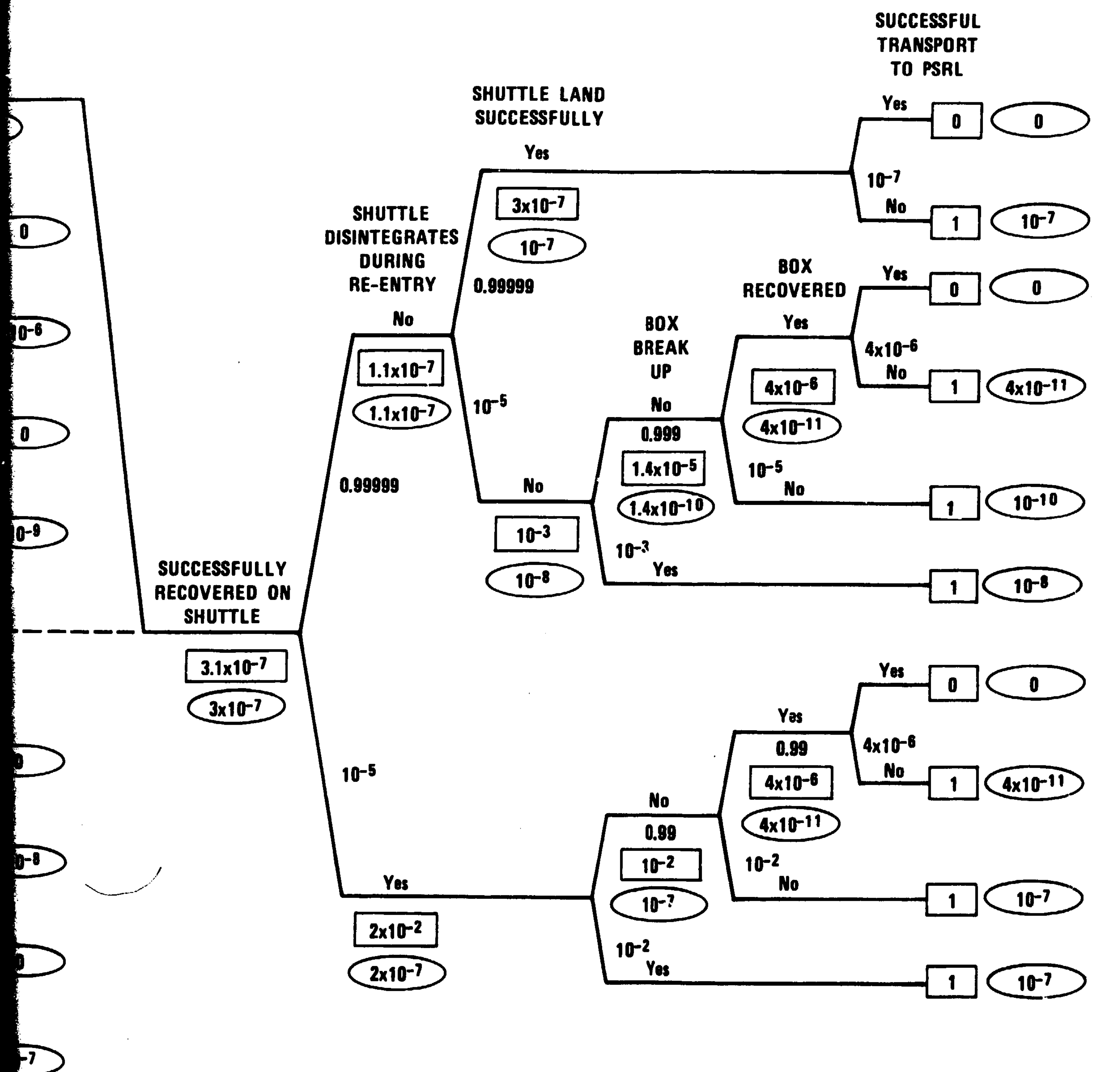


FIGURE E.1 PROBABILITY TREE FOR MAJOR EQUIPMENT FAILURE FOR AN ORBITAL RECOVERY OPTION (Continued)

FOLDOUT FRAME 2

Table E.1 (Concluded)

Event Title	Definition	Assessed Probability	Comments
Shuttle disintegrates during reentry	Shuttle disintegrates during reentry of the atmosphere.	10^{-5}	The shuttle atmospheric entry will be man-controlled and routine.
Shuttle lands successfully	After shuttle landing, the strongbox is intact and is successfully removed for transfer to the PSRL.	0.999 99	The U.S. commercial air carrier fleet has an accident involving a fatality about once in 10^6 operations (takeoff or landing).[18] We assume the shuttle to be at least one-tenth as safe.
Box breakup	The strongbox breaks apart, and at least one sample cannister is broken, spreading MO.	10^{-2} (if shuttle breaks up in atmosphere) 10^{-3} (if shuttle crash-lands)	The box will be built to withstand such eventualities.
Box recovered		0.99 (if shuttle disintegrates during re-entry) 0.99999 (if shuttle crash-lands)	If the shuttle crash-lands, there should be no trouble finding the box. If it breaks up in the atmosphere, the box may fall in the ocean and be lost.
Successful transport to PSRL		0.999 999 9 (nominal recovery), 0.9996 (otherwise)	We assume that the strongbox will be transported as a unit by a carefully thought-out method. Commercial air carriers have an accident involving a fatality once every 10^6 operations (takeoff or landing).[18] The box should withstand some crashes that cause fatalities. Non-nominal probability same as assumed in reference mission, Table B.1.

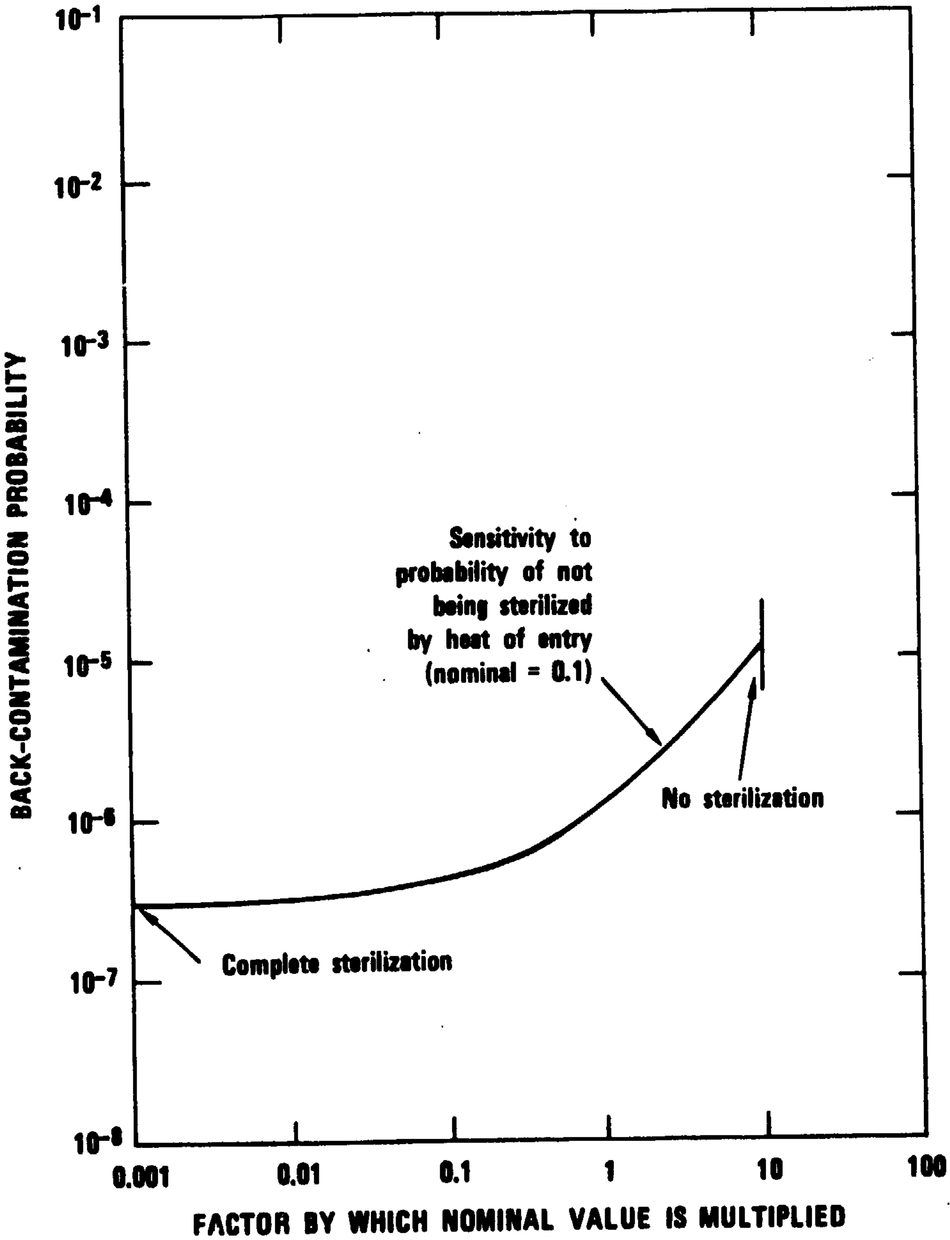


FIGURE E.2 SENSITIVITY TO PROBABILITY OF STERILIZATION BY ENTRY HEAT-UP

Roll-back of the probability tree in Figure E.1 shows that the probability of back-contamination due to major equipment failure is 1.4×10^{-6} for orbital recovery, compared to 1.6×10^{-4} for the reference mission involving direct Earth entry. We wish to emphasize that the estimates in this appendix are for illustrative purposes only; nevertheless, this indicates that this mission strategy may offer substantial improvement in back-contamination probability.

The reference mission has a probability of back-contamination due to leakage of 1.2×10^{-6}. The major contribution is due to leakage during Earth entry. Orbital recovery by means of a box sealed in orbit should reduce this probability substantially. (Care must be taken in the recovery procedure to guard against contamination of the space shuttle due to leakage.) Similarly, orbital recovery may be able to alleviate the major source of risk from surface contaminants, that is, atmospheric exposure to Martian organisms lodged on the exterior of the Earth-entry capsule. Table E.2 summarizes limits on the probability of

Table E.2

BACK-CONTAMINATION PROBABILITIES
FOR ORBITAL RECOVERY OPTION

Risk Category	Probability of Back-Contamination	Major Source of Risk
Major equipment failure	1.4×10^{-6}	EOC accidentally enters Earth atmosphere directly and sample is not sterilized
Leakage	$>2.7 \times 10^{-10}$*	Not analyzed
Surface contaminants	$>10^{-9}$*	Not analyzed

*Probability from reference mission not including Earth entry phase.

back-contamination for the three risk categories. The entries for leakage and surface contaminants are identical to those computed for the reference mission, not including contributions from the direct Earth-entry phase. We have not evaluated the specific contribution of the orbital recovery mission phase to these entries; therefore, the values indicated represent lower limits.

The added cost of orbital recovery from a shuttle-compatible orbit is estimated in Table E.3 to be \$30-60 million. This is to be compared to a cost in the one-billion-dollar range for the whole mission.

Table E.3

PRELIMINARY ESTIMATE OF ADDITIONAL COSTS OF DIRECT RECOVERY BY THE SPACE SHUTTLE OVER THE REFERENCE MISSION (DIRECT EARTH-ENTRY)

Source	Additional Cost ($ millions)
Construction of sample return box, shuttle launch and recovery, and ground operations.	$20-40
Extra propulsion and extra size of all mission stages in order to allow Earth orbital vehicle to enter a low-Earth (shuttle-compatible) orbit.	20
Savings due to elimination of task force to perform the air snatch on the Earth-return vehicle.	?
Total extra cost (rough estimate)	$30-60

E.2 Summary of Results

Table E.4 summarizes the results of the analysis. This preliminary comparison of the orbital recovery option with the nominal reference mission design indicates that orbital recovery may have a substantially lower probability of potential back-contamination, a somewhat greater mission complexity, and a higher dollar cost, or may require a reduction in the size of the returned sample. These estimates need to be confirmed by more careful analysis, including an analysis of the option of orbital recovery from other orbits, for instance, a 24-hour elliptical orbit.

Table E.4

COMPARISON OF NOMINAL MISSION WITH TWO OPTIONS INVOLVING ORBITAL RECOVERY

Mission	Total Probability of Back-Contamination	Cost Differential Above Nominal Mission ($ millions)	Scientific Value
Reference mission (direct Earth entry)	1.6×10^{-4}	0	Nominal
Orbital recovery--24-hour elliptical orbit	Not assessed. Possibly somewhat above 1.4×10^{-6} due to extra complexity of mission.	Not investigated	Nominal
Orbital recovery--low orbit (shuttle-compatible)	1.4×10^{-6}	$30-60	Nominal

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